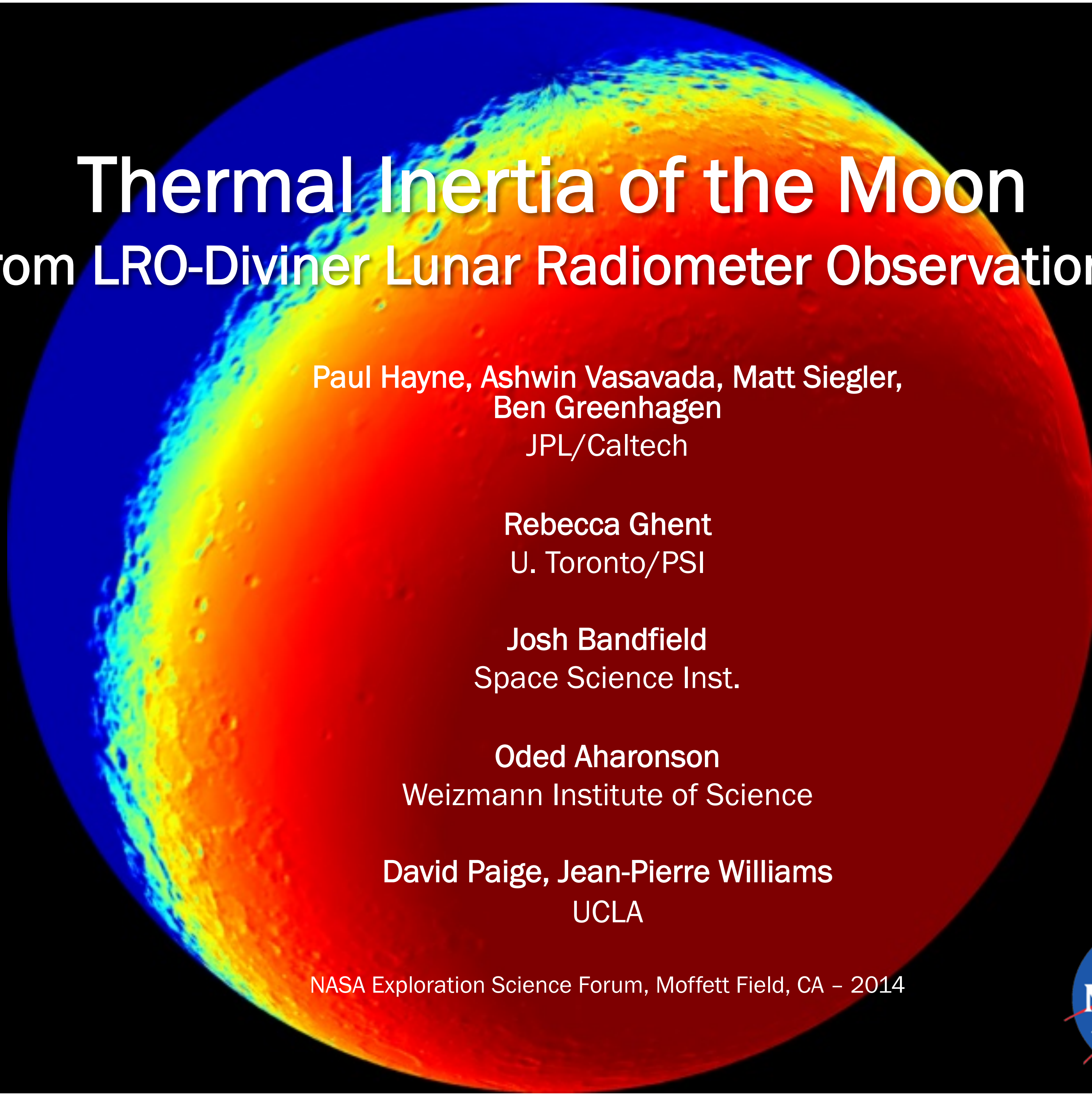


Thermal Inertia of the Moon
from LRO-Diviner Lunar Radiometer Observations

Paul Hayne, Ashwin Vasavada, Matt Siegler, Ben Greenhagen
JPL/Caltech

Rebecca Ghent
U. Toronto/PSI

Josh Bandfield
Space Science Inst.

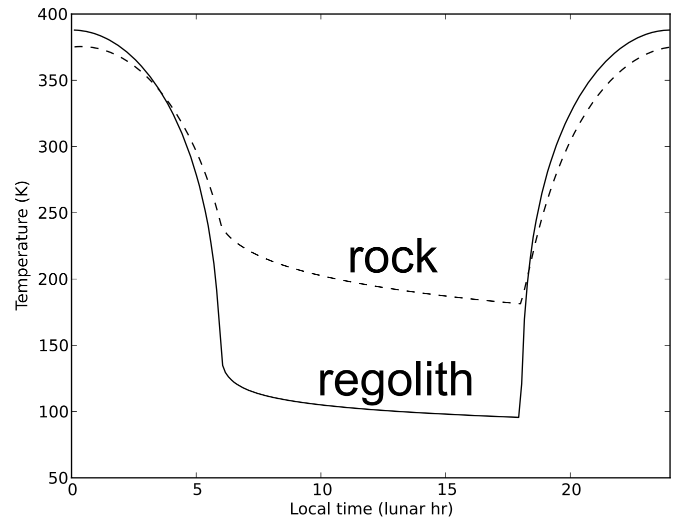
Oded Aharonson
Weizmann Institute of Science

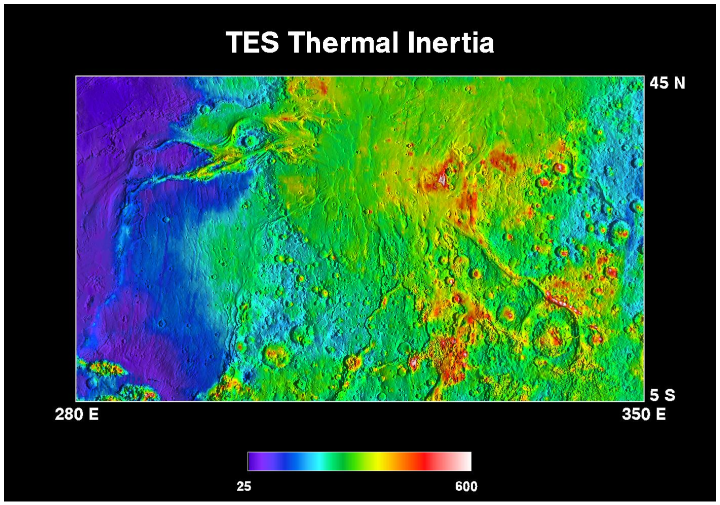
David Paige, Jean-Pierre Williams
UCLA

NASA Exploration Science Forum, Moffett Field, CA – 2014

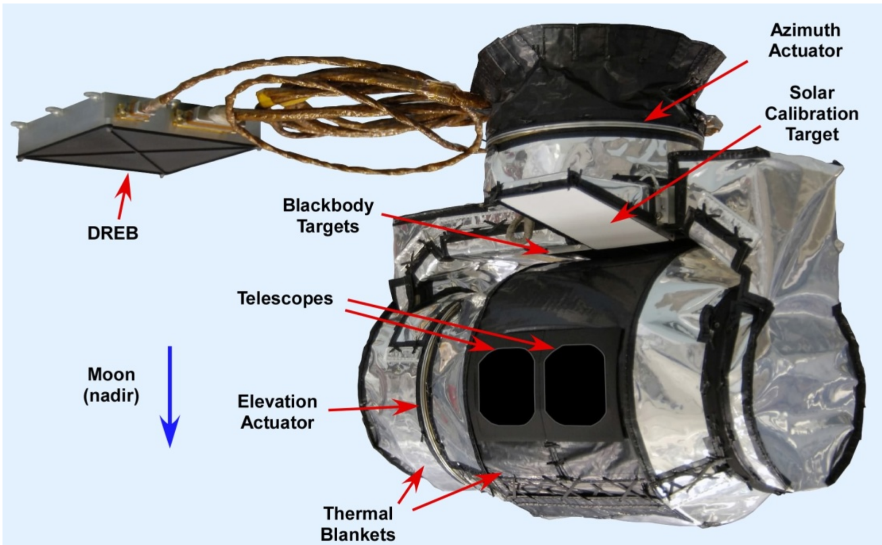
Background: Thermal Inertia

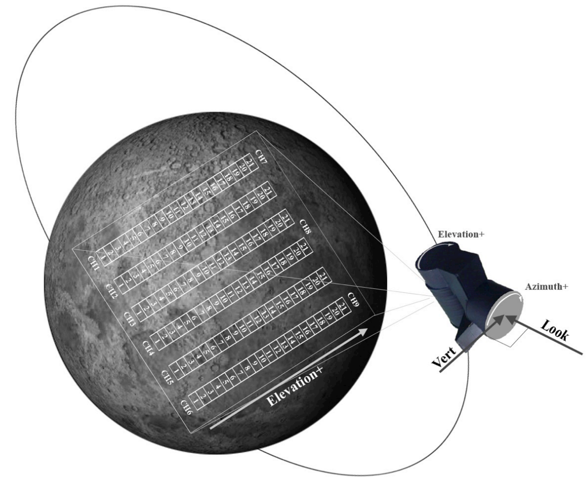
- Thermal inertia (TI) is a physical parameter describing the tendency of a material to resist changes in temperature (formally: $\sqrt{k\rho c_p}$)
- Dust and sand = low TI, rocks and densely packed grains = high TI
- Orbital remote sensing highly successful for determining TI on Mars; used for geology and landing site selection

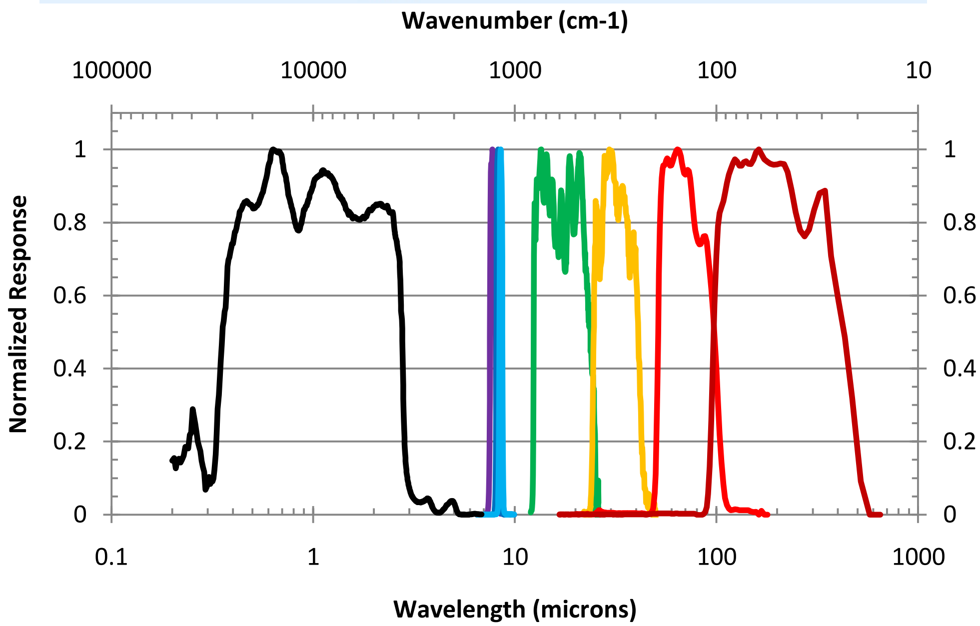




LRO Diviner Overview





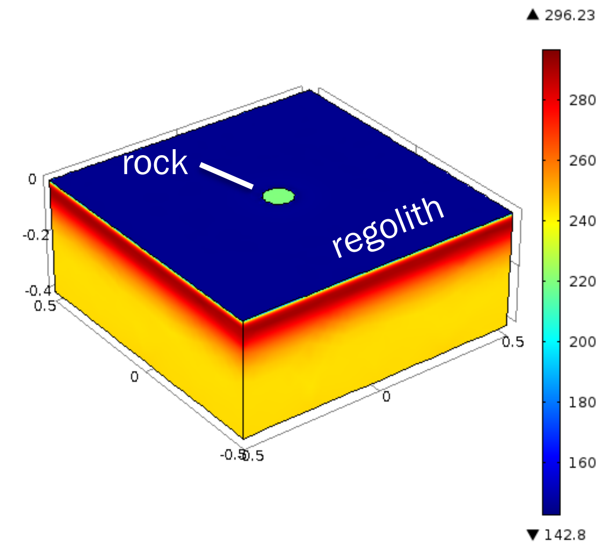


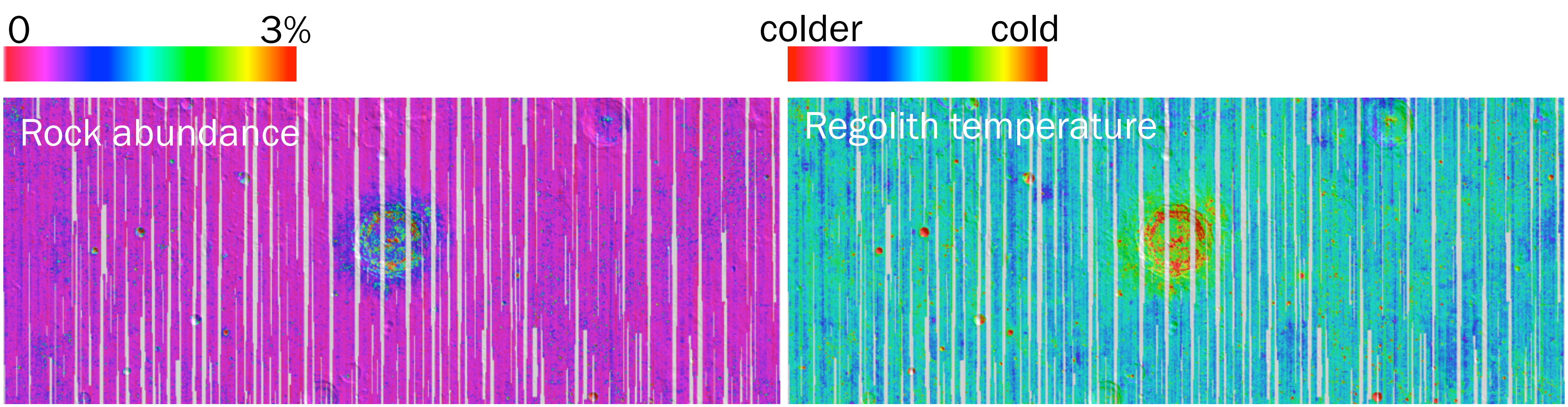
Observation Strategy	Primarily nadir pushbroom mapping
Detectors	Nine 21-element linear arrays of uncooled thermopile detectors
Fields of view	Detector Geometric IFOV: 6.7 mrad in-track 3.4 mrad cross track 320 m on ground in track for 50 km altitude 160 m on ground cross track for 50 km altitude Swath Width (Center to center of extreme pixels): 67 mrad; 3.4 km on ground for 50 km altitude

Rock Abundance & Regolith Temperature

- Use Diviner nighttime brightness temperatures at different wavelengths to separate surface rocks from regolith

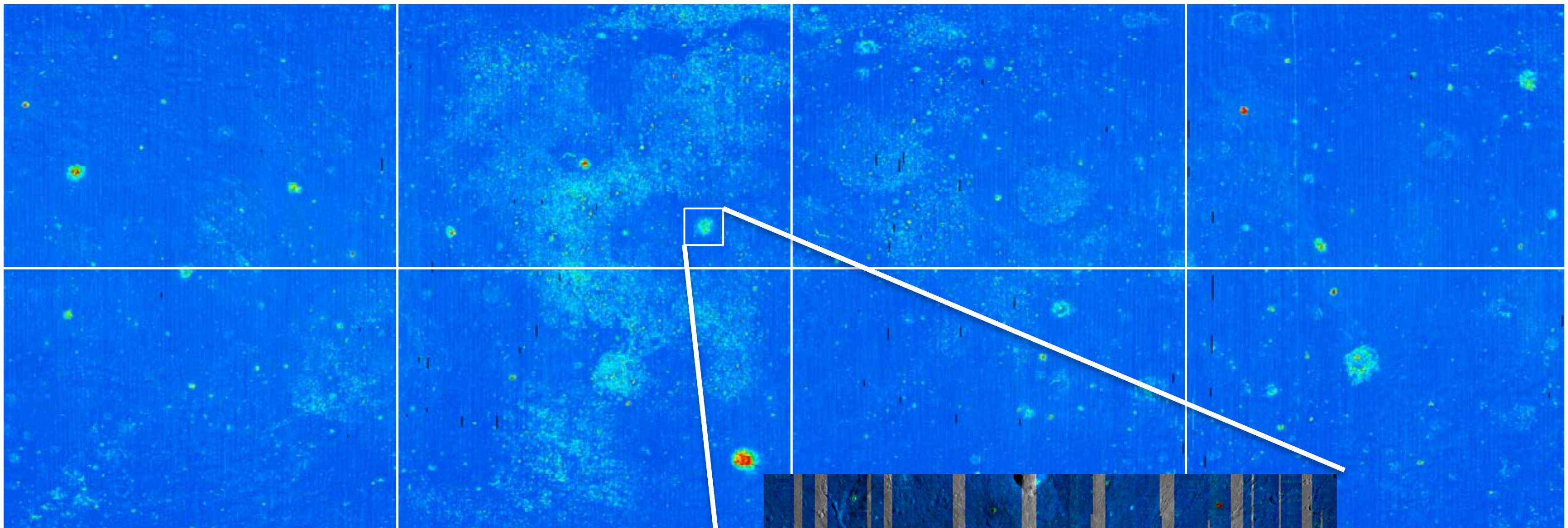
- Two free parameters:
  1. Rock concentration
  2. Regolith temperature



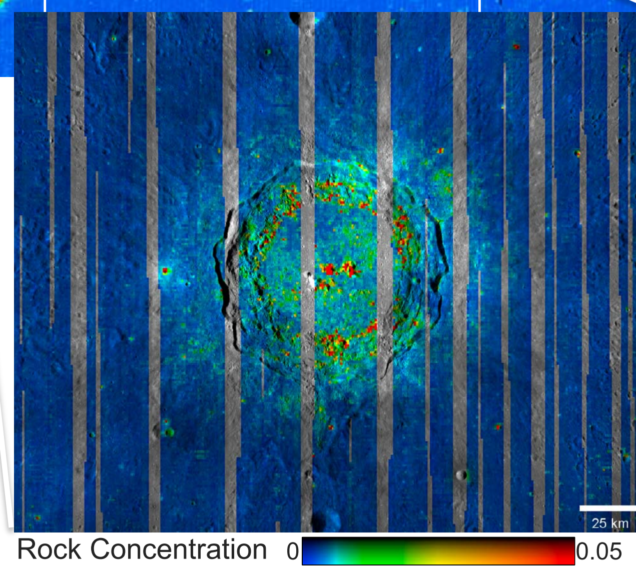


Bandfield et al. (2011)

Surface Blocks



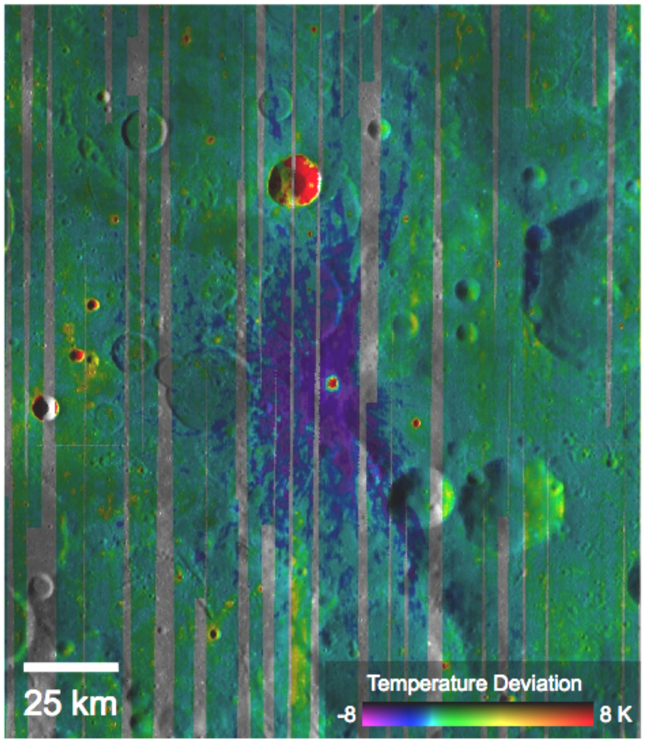
Rock Concentration (0-0.05)

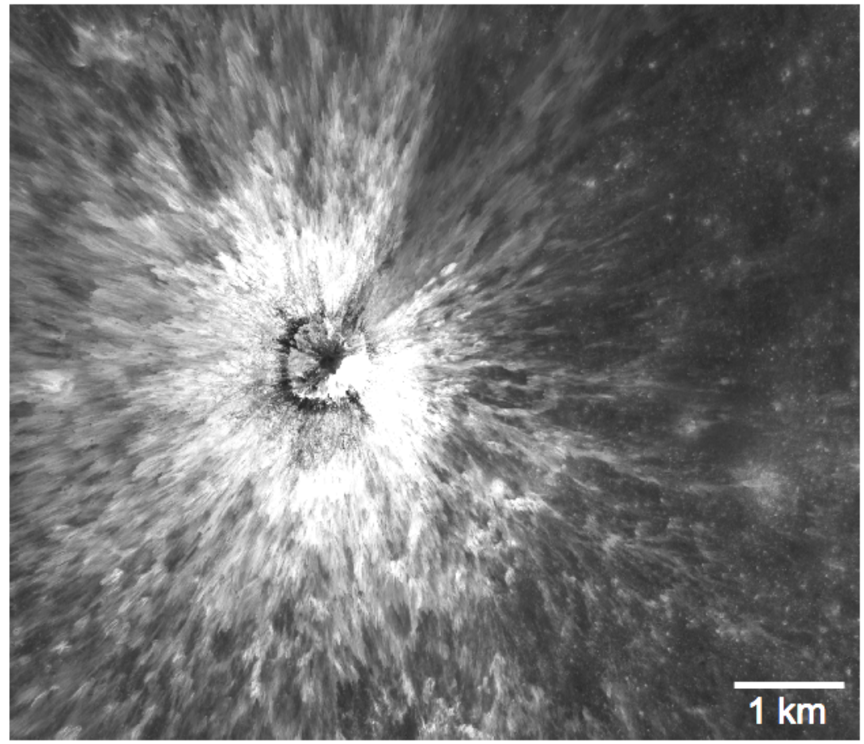


Copernicus crater

Bandfield et al., *JGR* (2011)

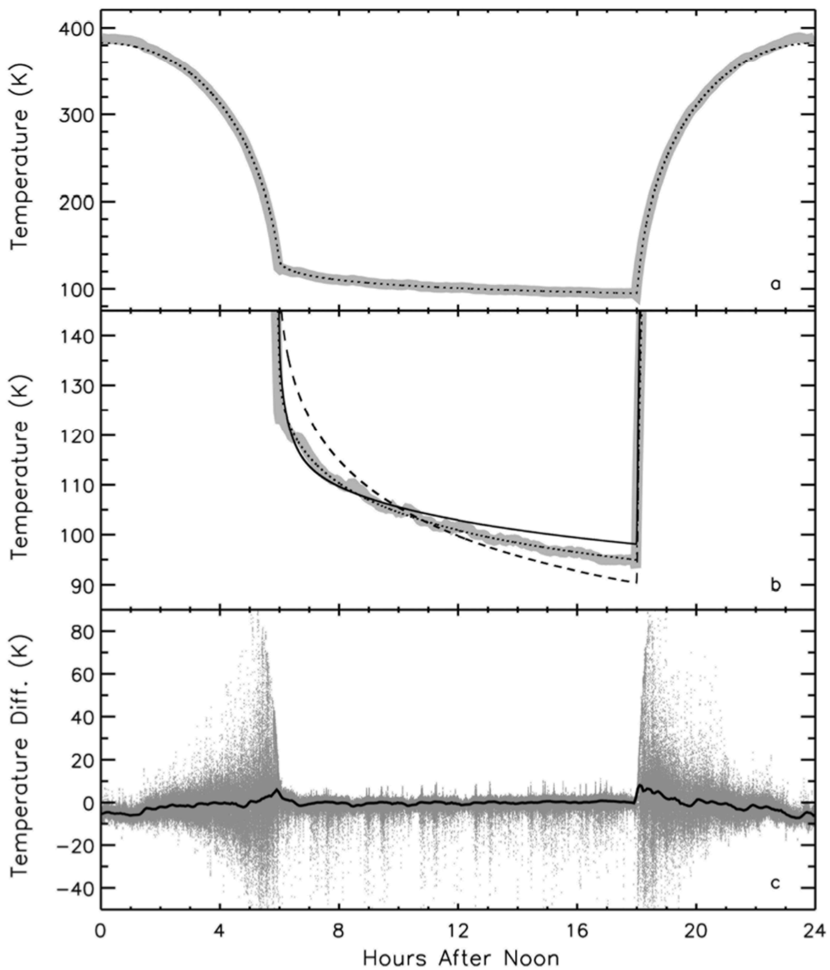
Diviner “Cold Spots”

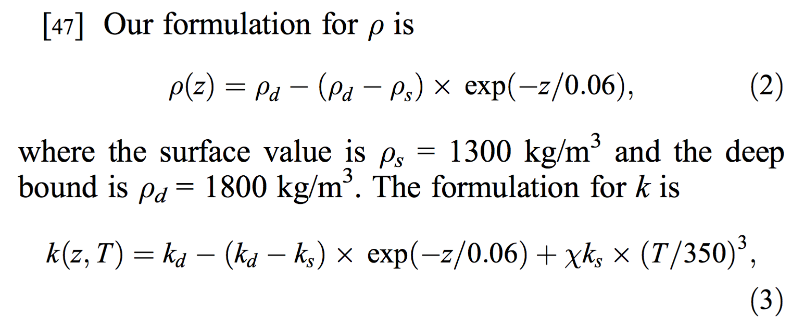




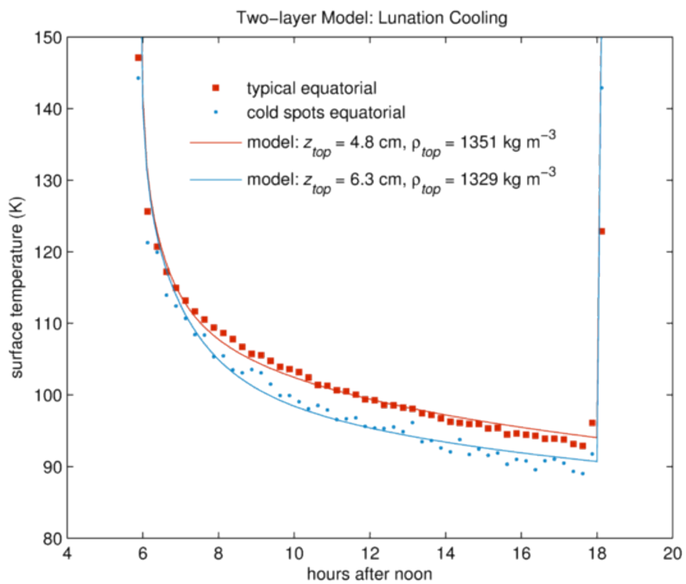
- Large (100’s of crater radii) regions around some fresh craters are unusually cold at night
- 400+ documented cases
- Cannot be ejecta due to volume of material required
- Current best hypothesis is *in situ* decompression of regolith due to turbulent vapor or scouring by ballistic particles (Bandfield et al., *submitted,* 2013)

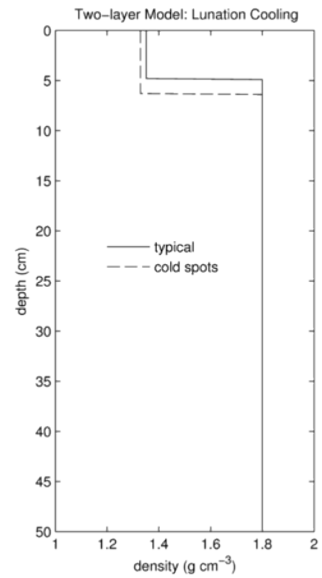
Equatorial Results from Vasavada *et al*. (2012)

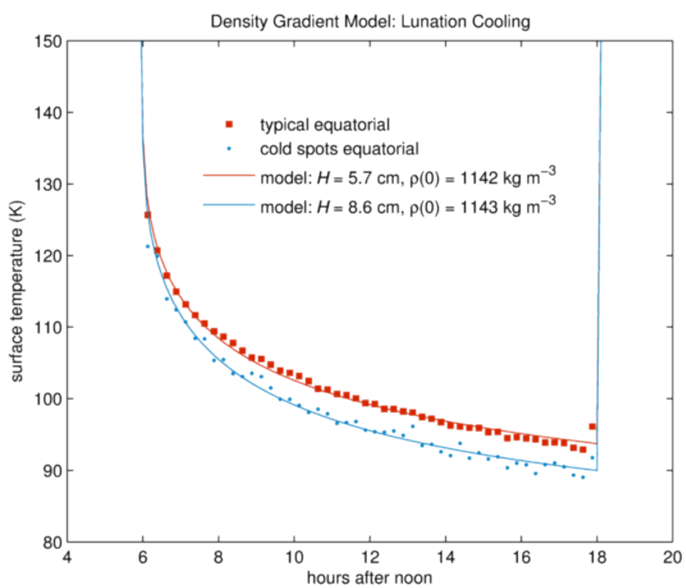


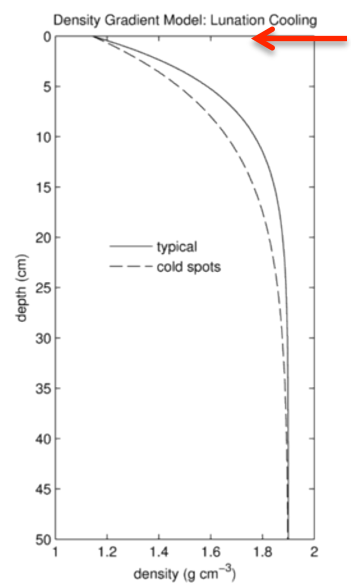


- Small correction: the radiative term should be proportional to the local solid conductivity, not the (constant) surface value


Two–layer Model: Lunation Cooling
typical equatorial
cold spots equatorial
model: z_{top} = 4.8 cm, ρ_{top} = 1351 kg m^{-3}
model: z_{top} = 6.3 cm, ρ_{top} = 1329 kg m^{-3}
surface temperature (K)
hours after noon


Two–layer Model: Lunation Cooling
typical
cold spots
depth (cm)
density (g cm^{-3})

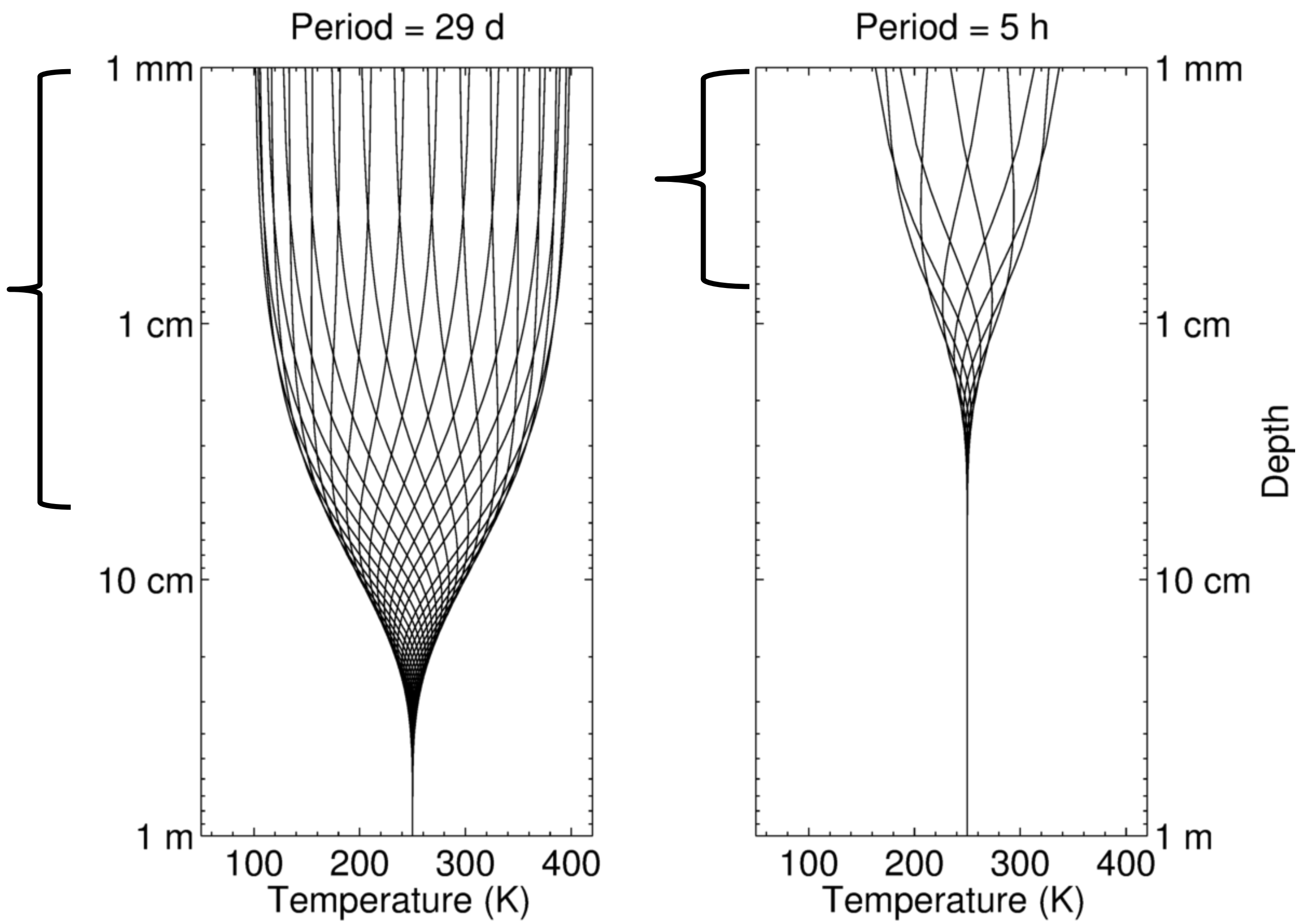

Density Gradient Model: Lunation Cooling
typical equatorial
cold spots equatorial
model: H = 5.7 cm, $\rho(0)$ = 1142 kg m^{-3}
model: H = 8.6 cm, $\rho(0)$ = 1143 kg m^{-3}
surface temperature (K)
hours after noon


Density Gradient Model: Lunation Cooling
typical
cold spots
depth (cm)
density (g cm^{-3})

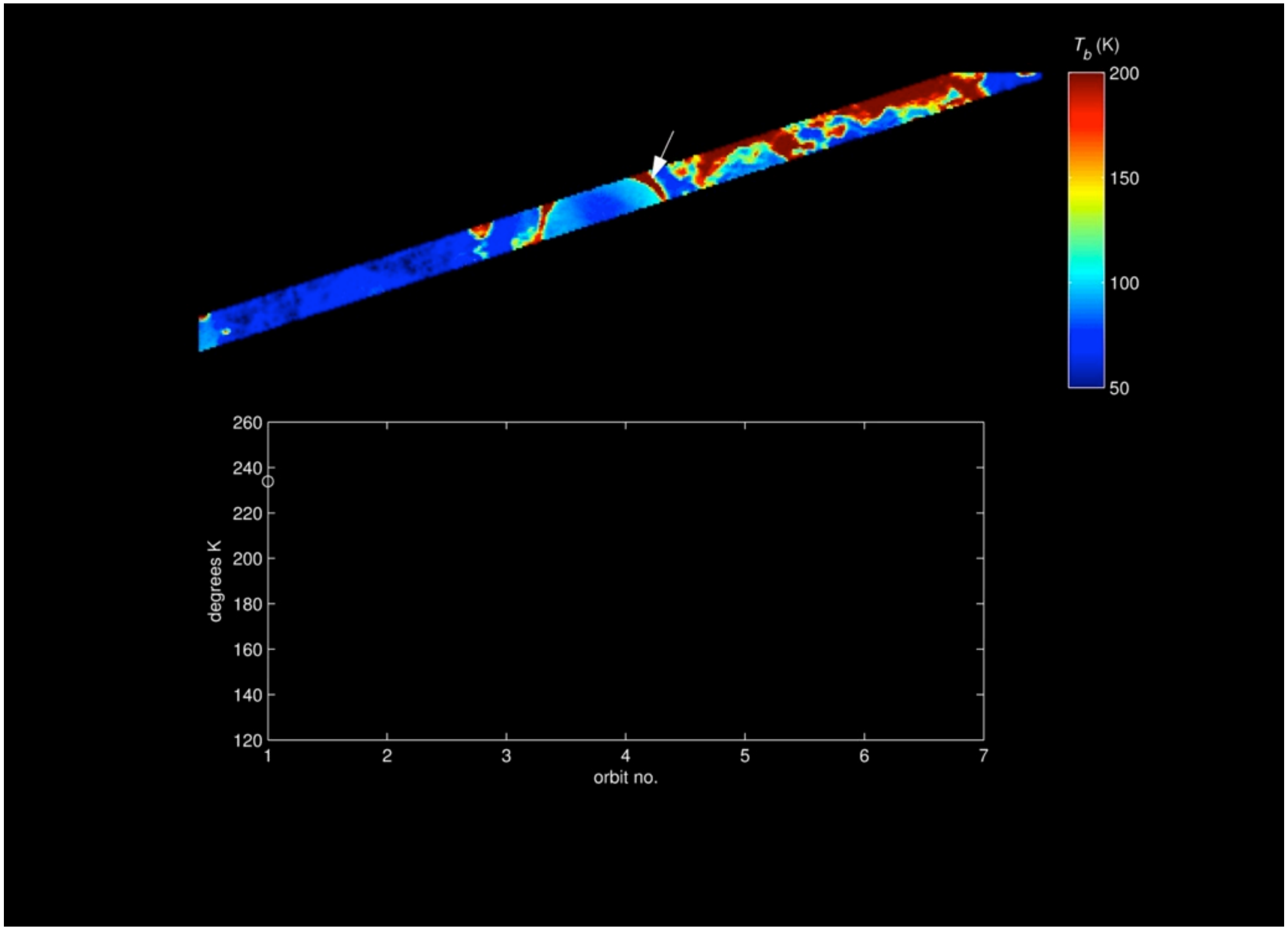

TOP

Thermal Skin Depth

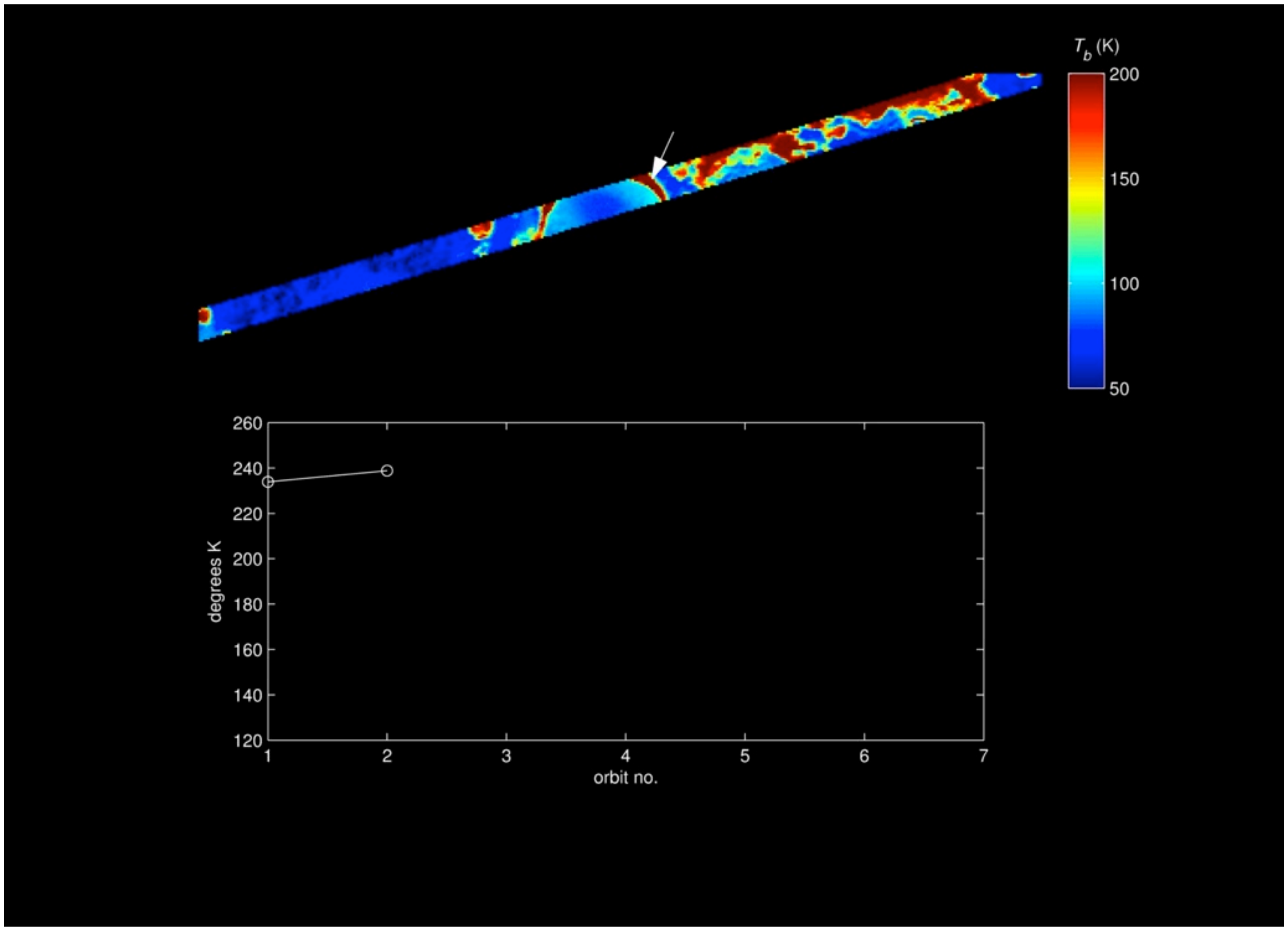
$z_{skin} = \sqrt{(2\kappa/\omega)}$
$\Delta T \sim e^{-z/zskin}$



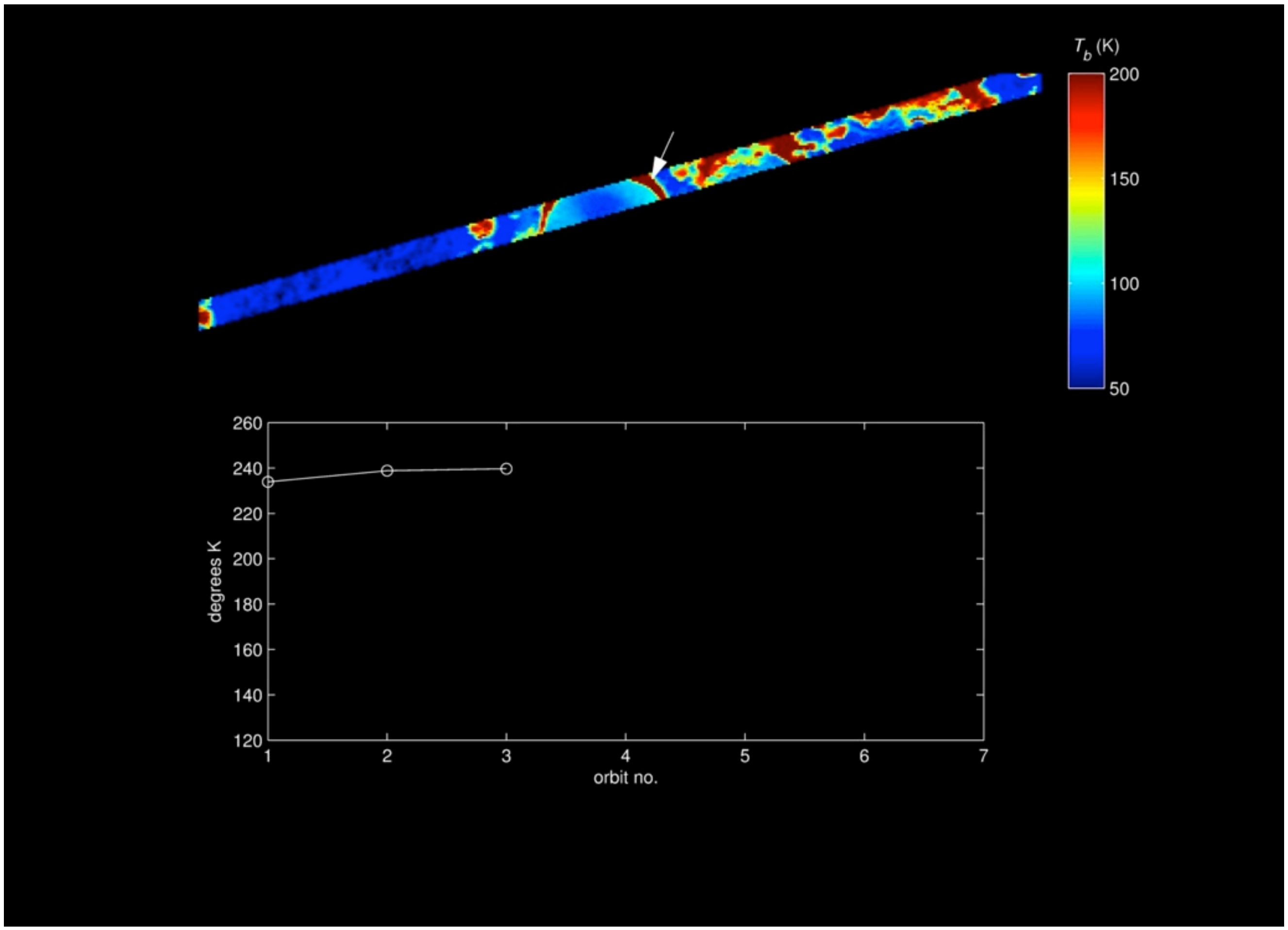
Eclipse cooling



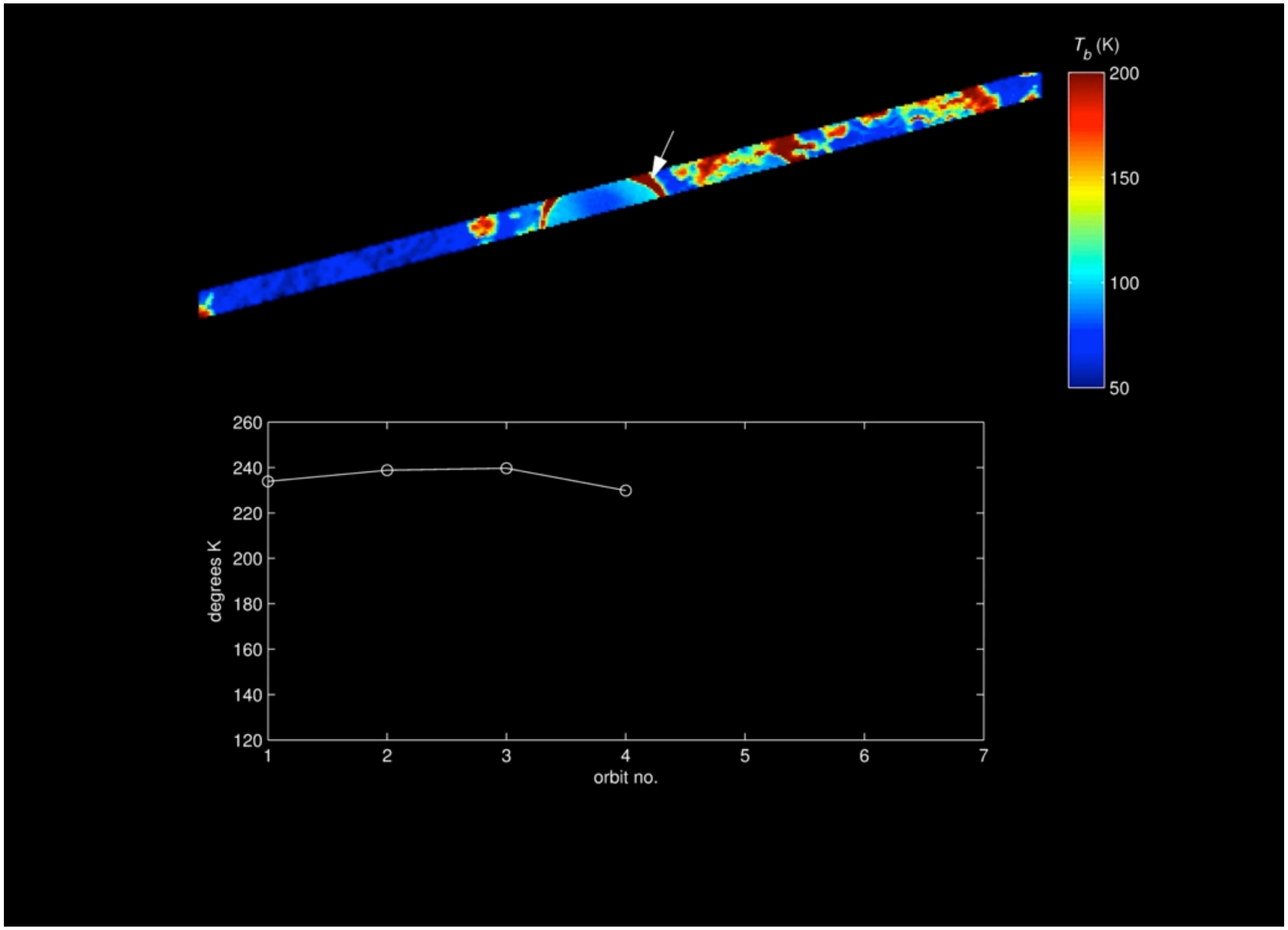
Eclipse cooling



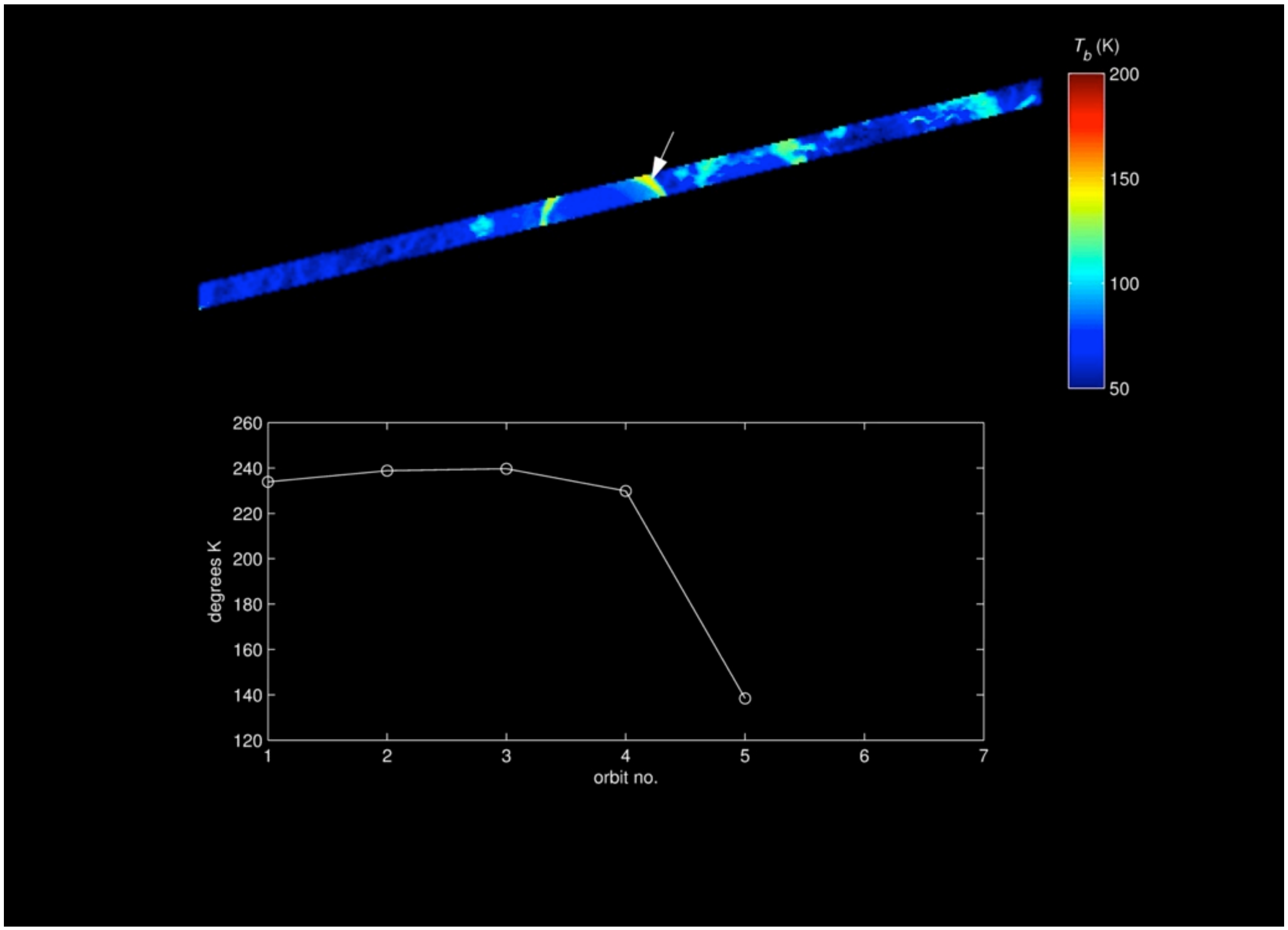
Eclipse cooling



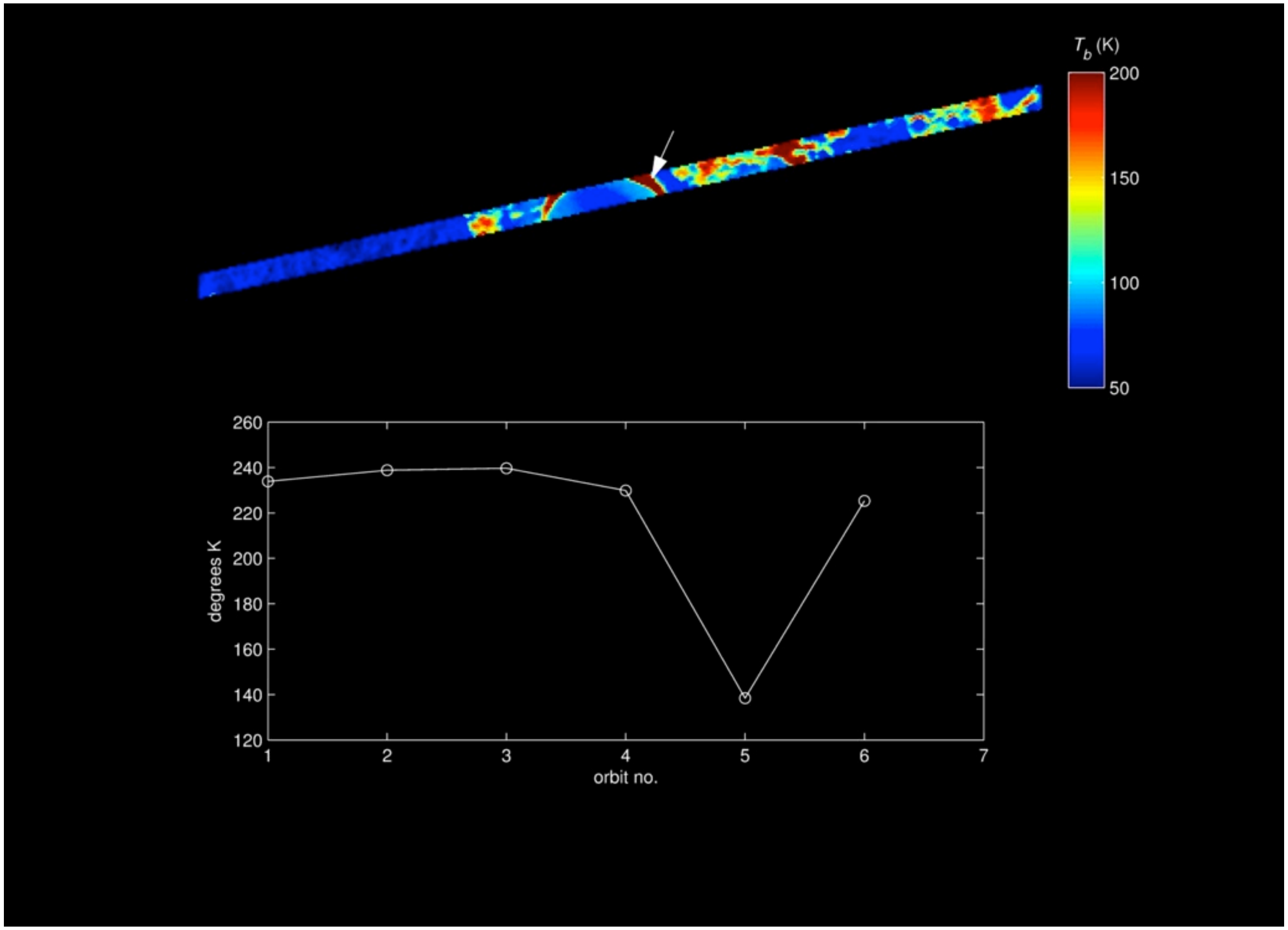
Eclipse cooling



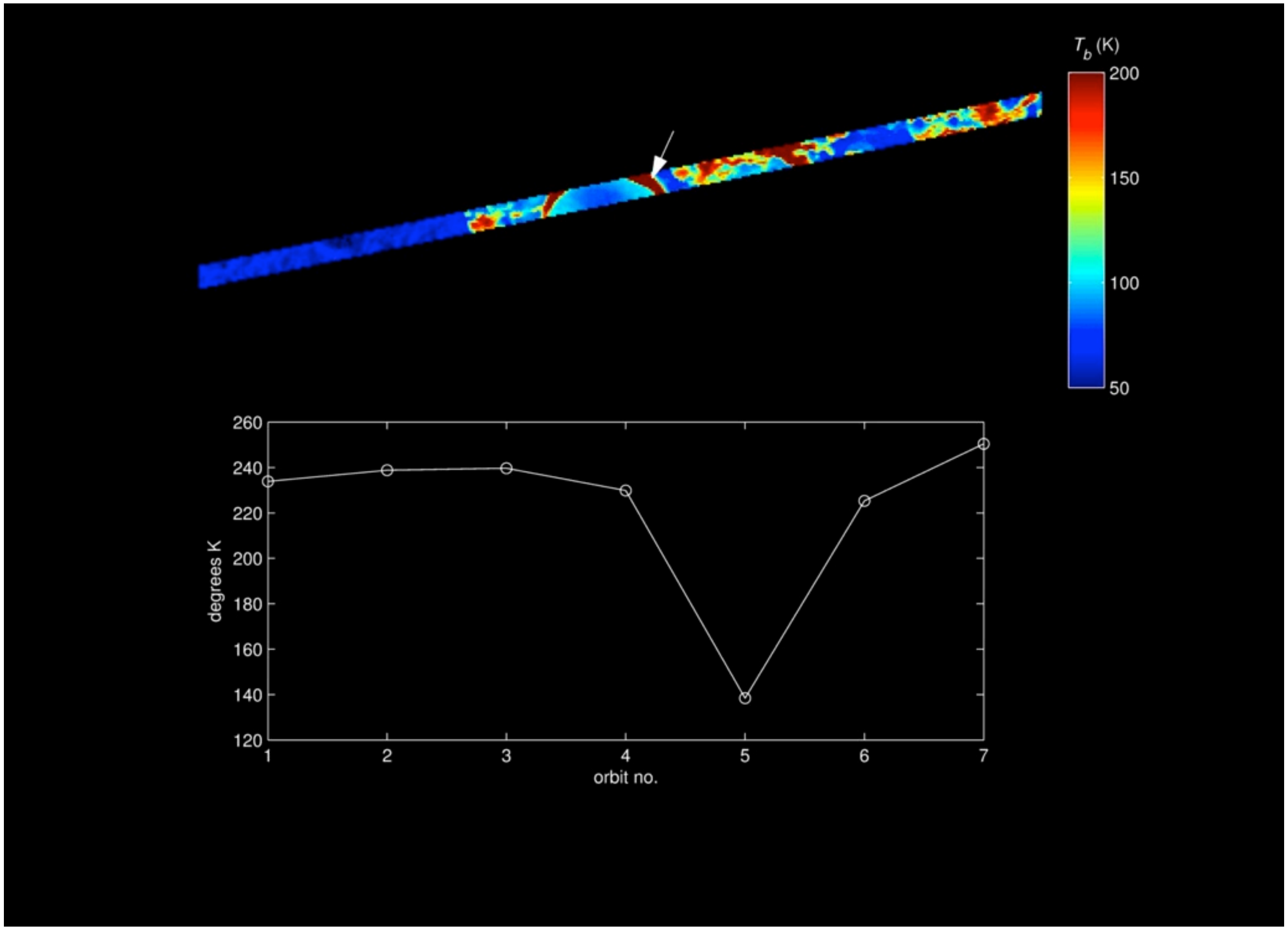
Eclipse cooling



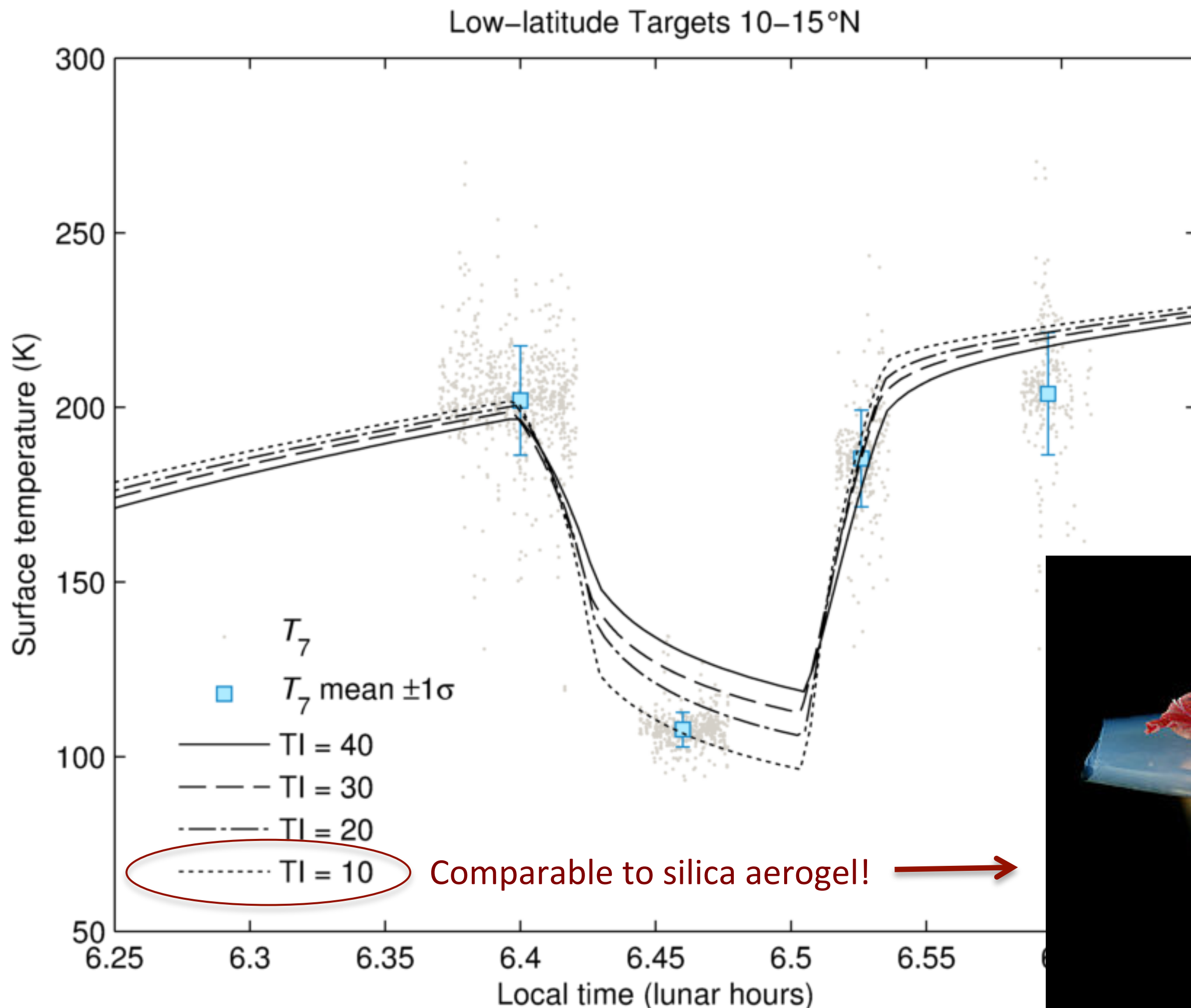
Eclipse cooling



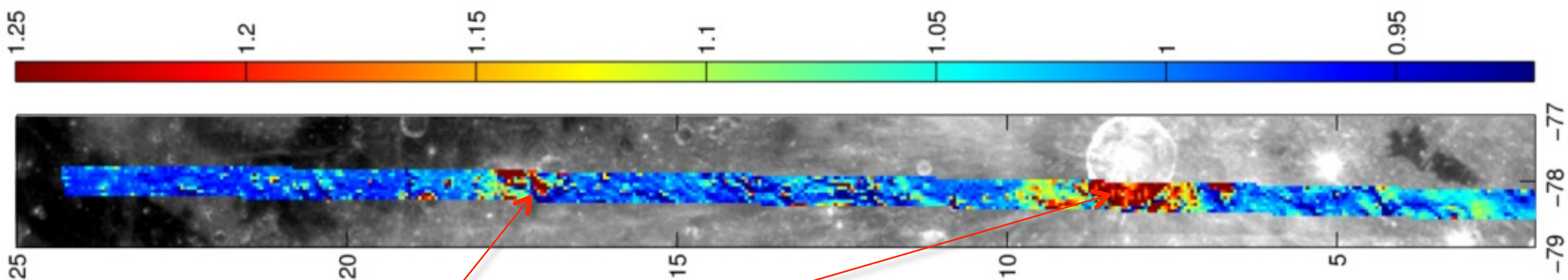
Eclipse cooling



Eclipse Cooling



Eclipse Thermal Inertia



Fresh, rocky craters + ejecta

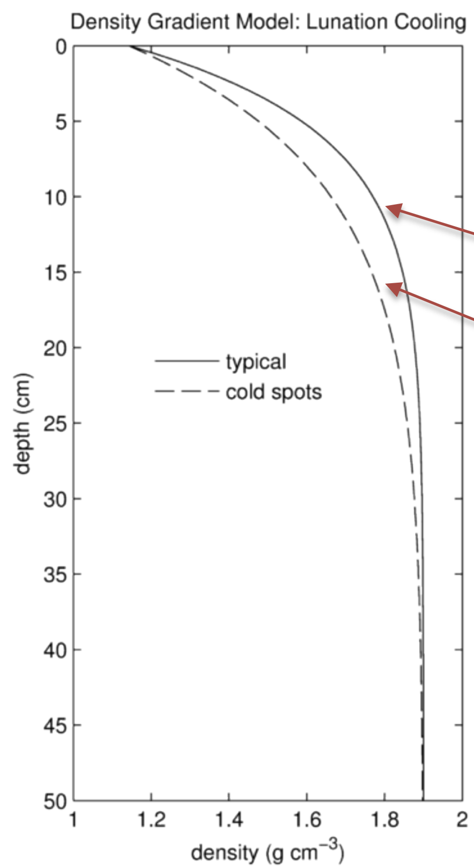
- Rocky spots have ~2x the average TI
- If rocks make up 1 – 5% of the area in "rocky" spots, and assuming linear mixing, then individual rocks have TI ~ 20 – 100x regolith
- If we believe the average TI ~ 15 SI units, then rocks have TI ~ 300 – 1500 units

Best-fit Parameter Values

Parameter	Vasavada et al. (2012)	Hayne et al. (2013)	Constraints
ρ_s, ρ_d	1300, 1800 kg/m^3	1100, 1800 kg/m^3	Apollo core samples (Carrier et al., 1975)
k_s, k_d	6.0e-4, 7.0e-3 W/m/K	6.0e-4, 3.0e-3 W/m/K	Diviner nighttime temps
χ	2.7	2.7	Latitude dependence of T
Albedo: a,b	0.045, 0.14	0.045, 0.14	LROC? Diviner solar?
ε	0.98	0.95	Diviner IR
Q	16 mW/m^2	17 mW/m^2	Apollo heat flow
H	0.06	Variable; avg ~ 0.06	

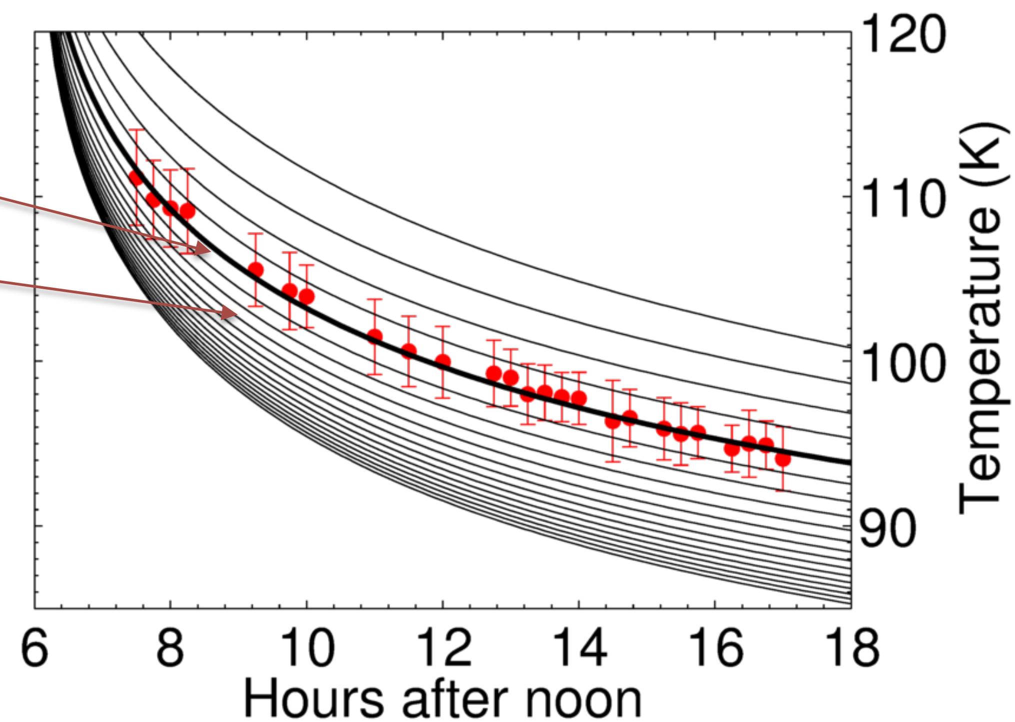
Regolith Profile Fits: "H-parameter"

$$\rho(z) = \rho_d - (\rho_d - \rho_s)e^{-z/H}$$

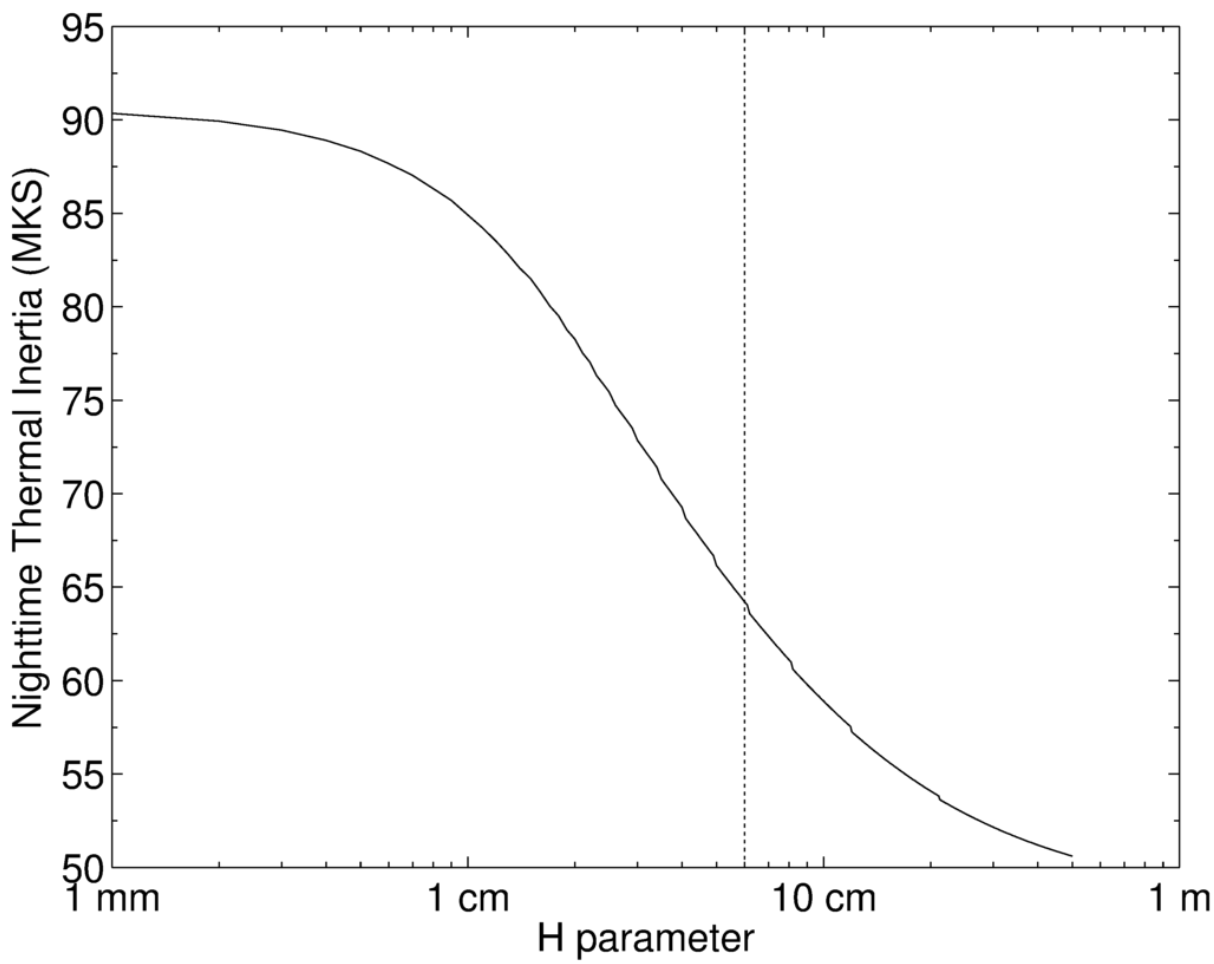


$H \approx 6$ cm

$H \approx 9$ cm

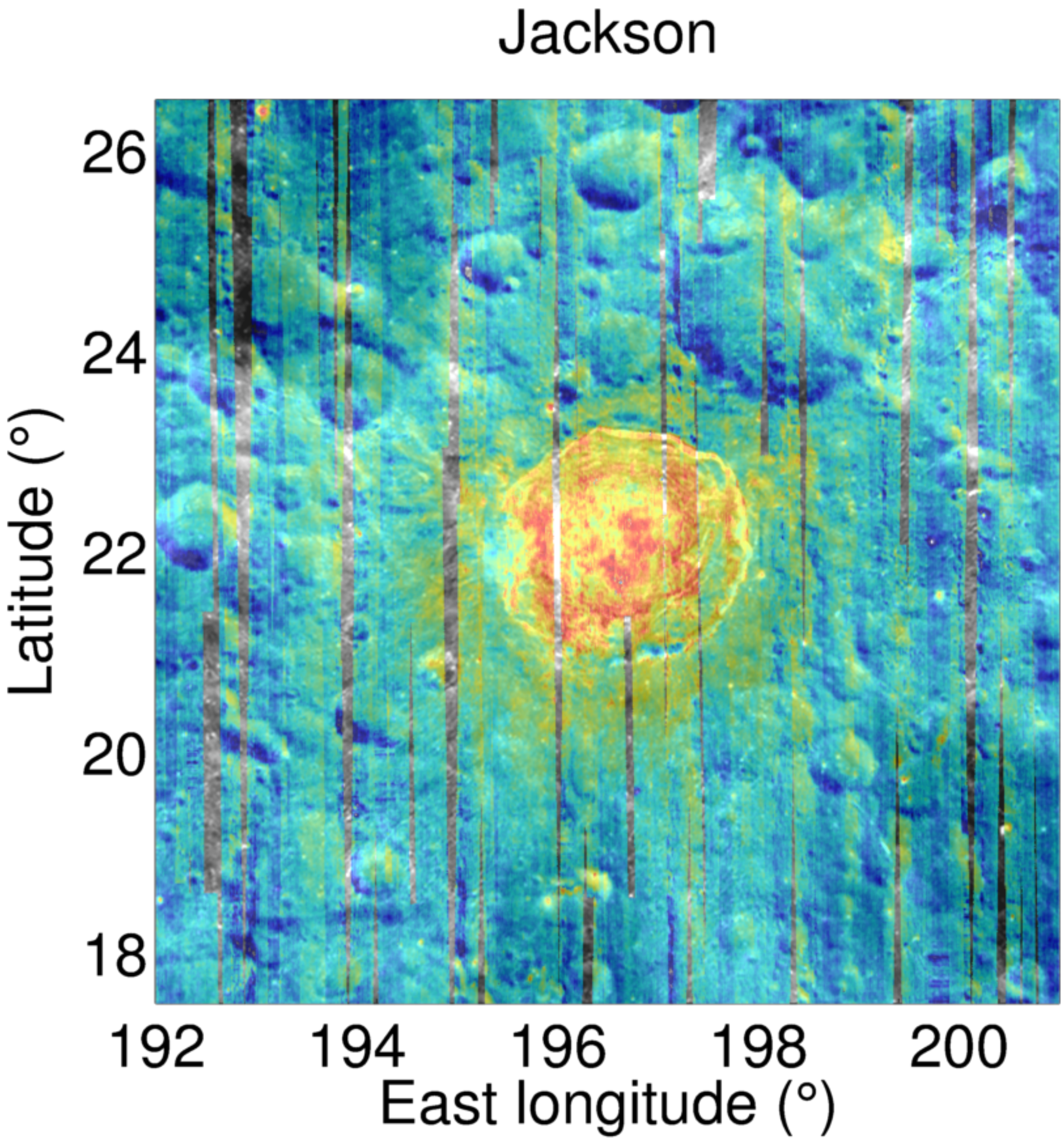


'H' -> Thermal Inertia Conversion

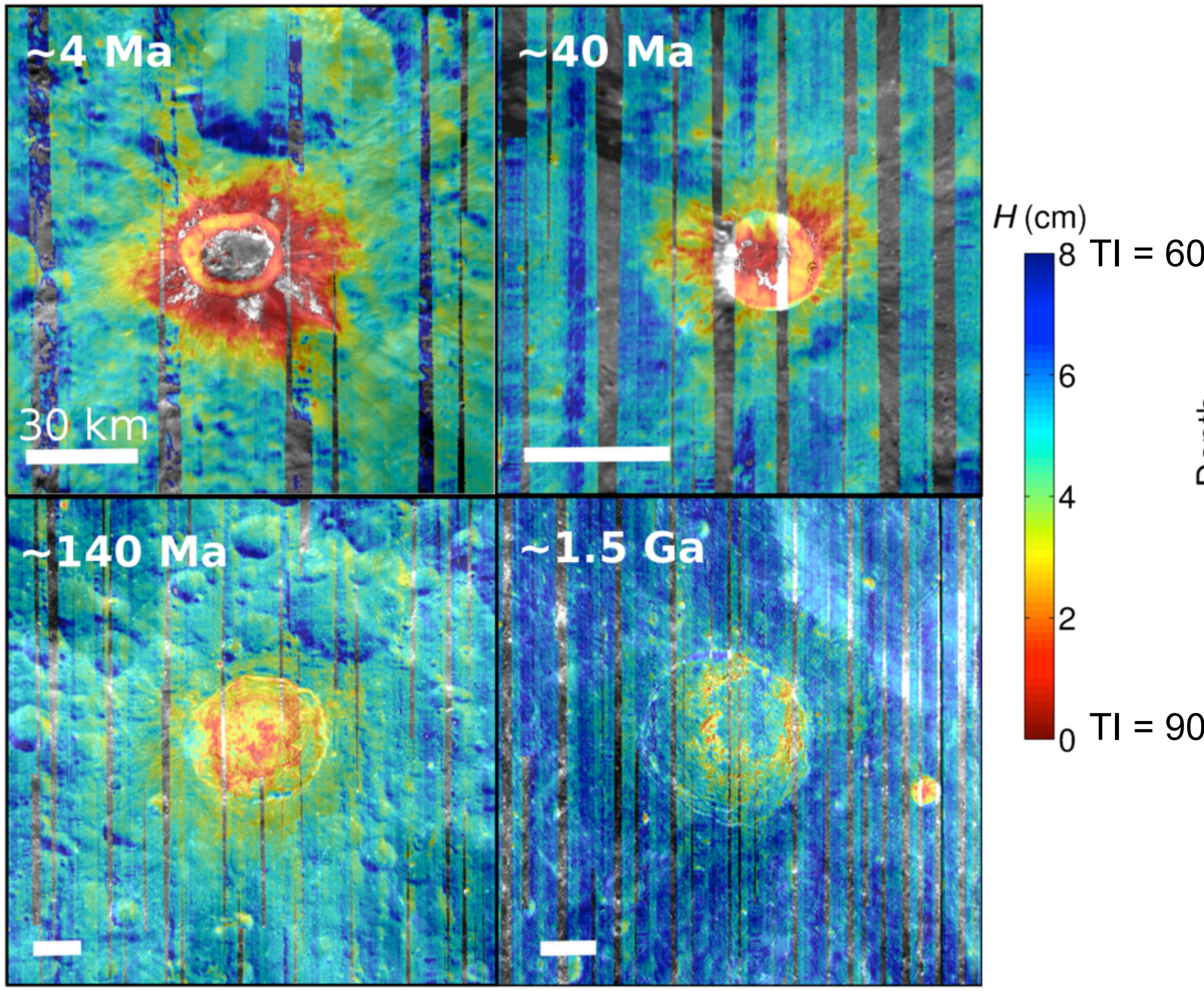


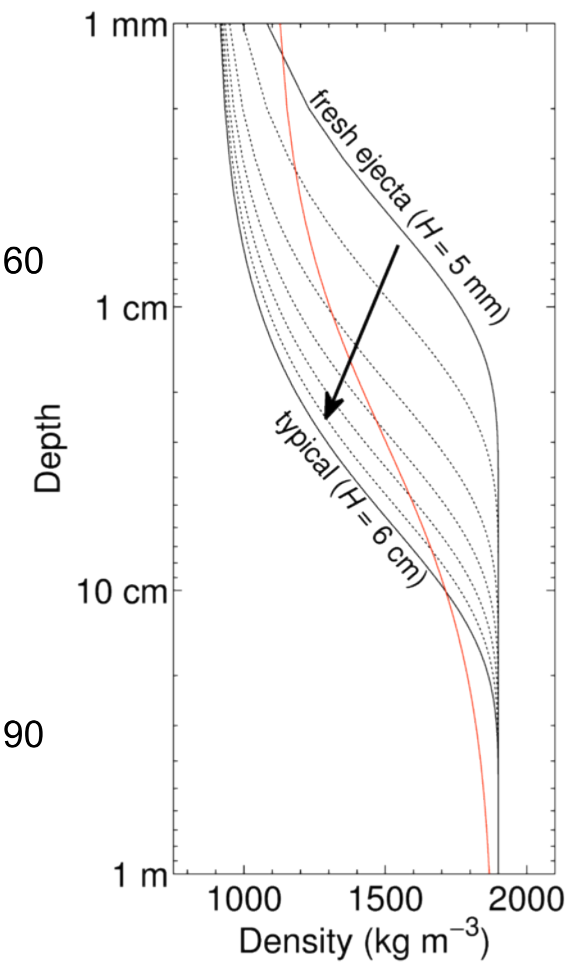
Applications: Regolith Formation

- Variations in H-parameter/thermal inertia indicate real differences in regolith density associated with geologic features
- Do these variations constrain models of regolith formation and evolution?
- See paper by R. Ghent (*Geology*, 2014)

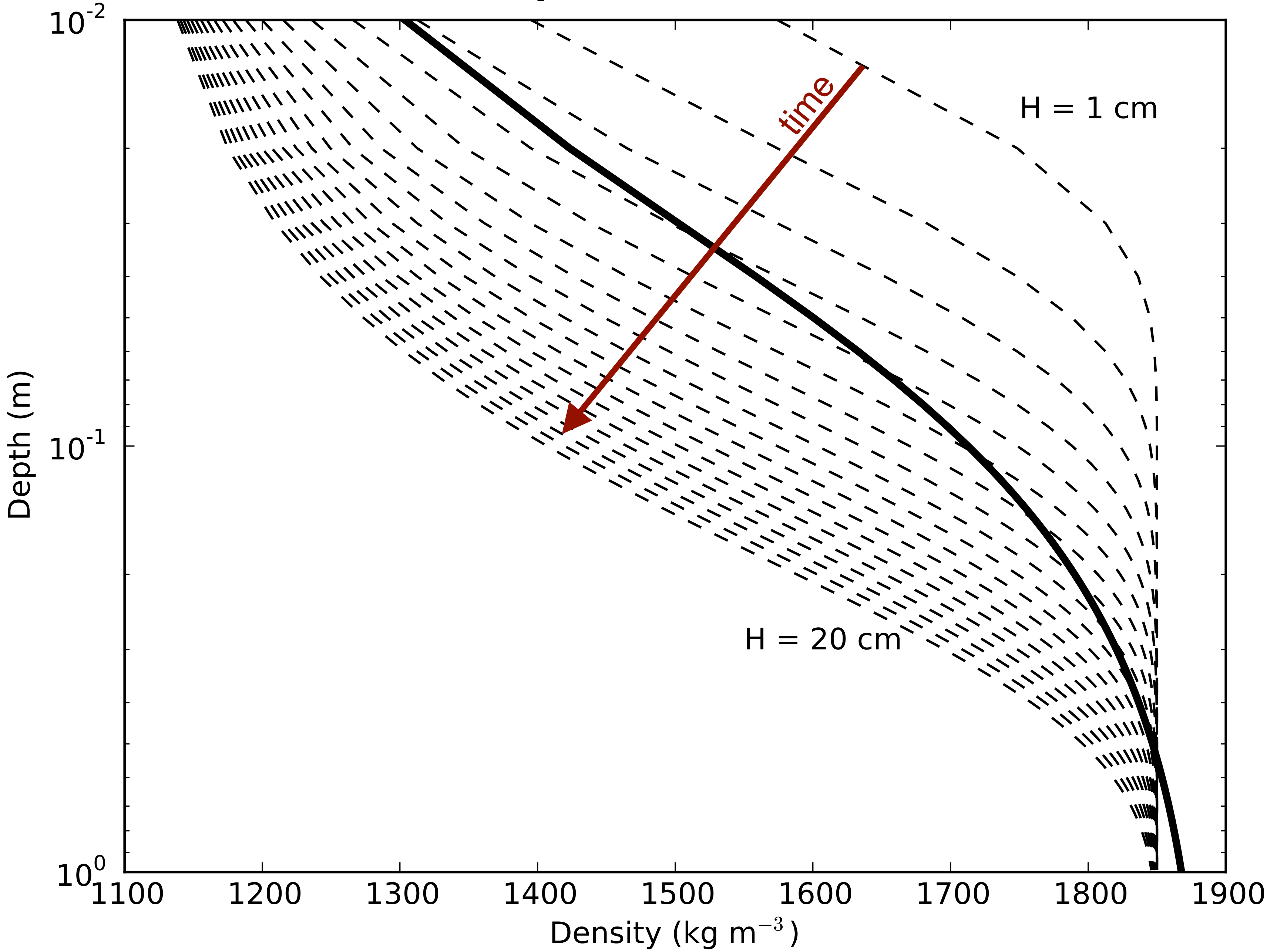

Jackson
Latitude (°)
26
24
22
20
18
192
194
196
198
200
East longitude (°)

Crater Evolution (*Ghent et al.*, 2013)





“H-parameter”



time
H = 1 cm
H = 20 cm
Depth (m)
10^{-2}
10^{-1}
10^{0}
1100
1200
1300
1400
1500
1600
1700
1800
1900
Density (kg m^{-3})

Regolith Formation Models

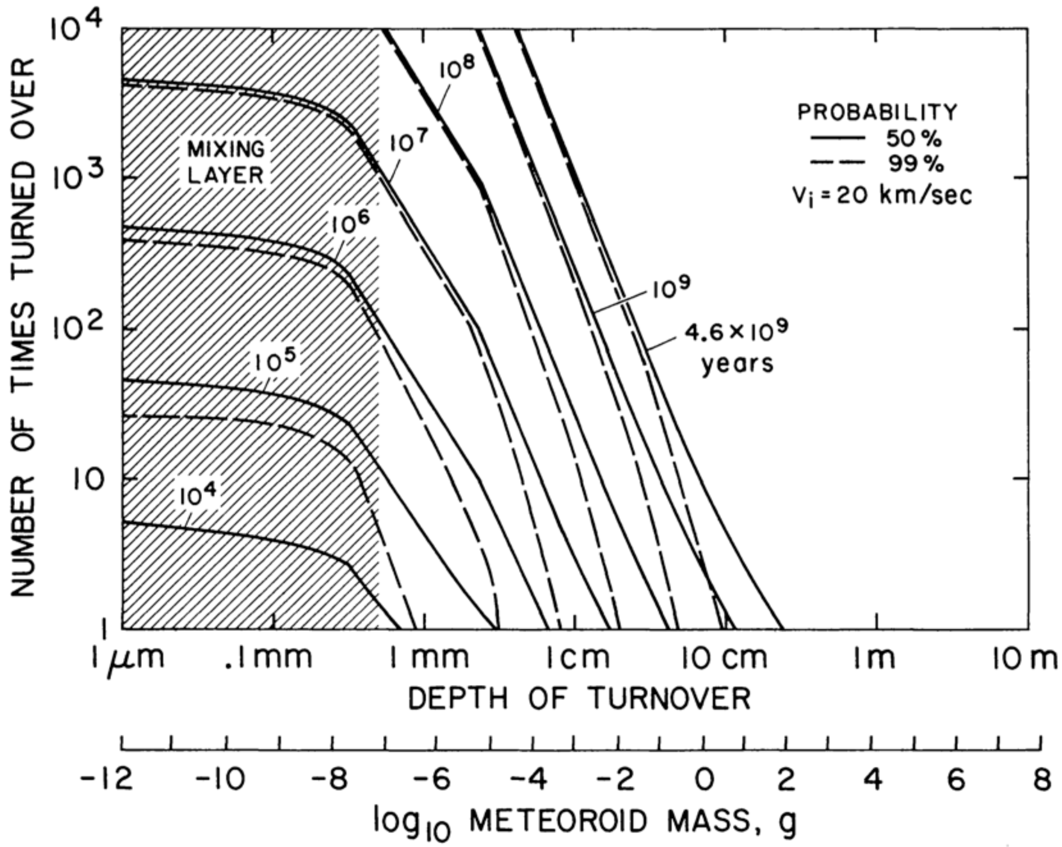
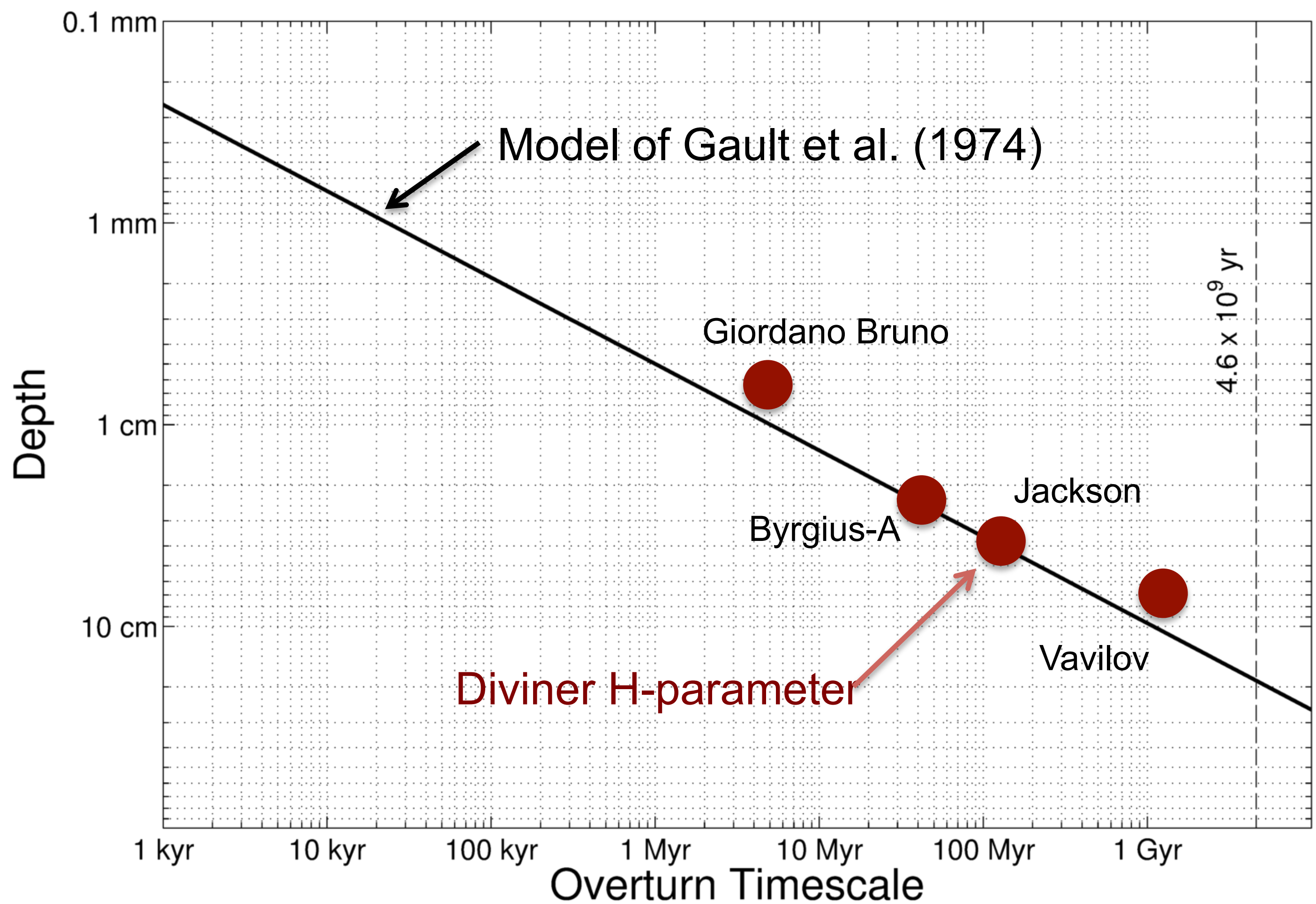


Fig. 9. Number of times n the regolith is turned over as a function of turnover depth and meteoroid mass, flux constant.

Gault et al. (1974) regolith gardening model calculates probability of overturn at each depth, after a certain period of time

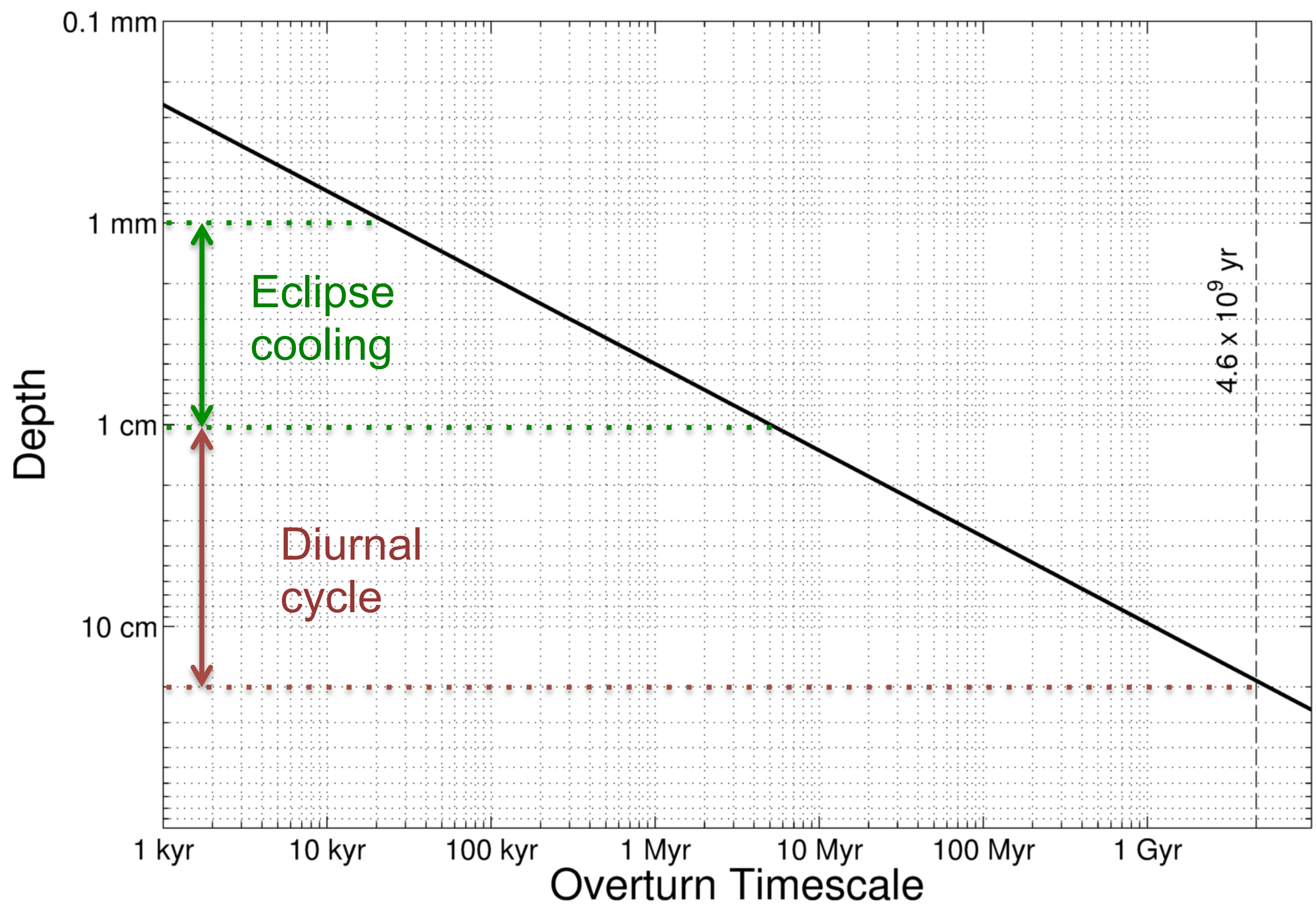
log(N) ~ -log(depth)
→ Expect exponential increase in density w/ depth if 'overturn' decreases density

Crater Ages vs. Upper Regolith Thickness



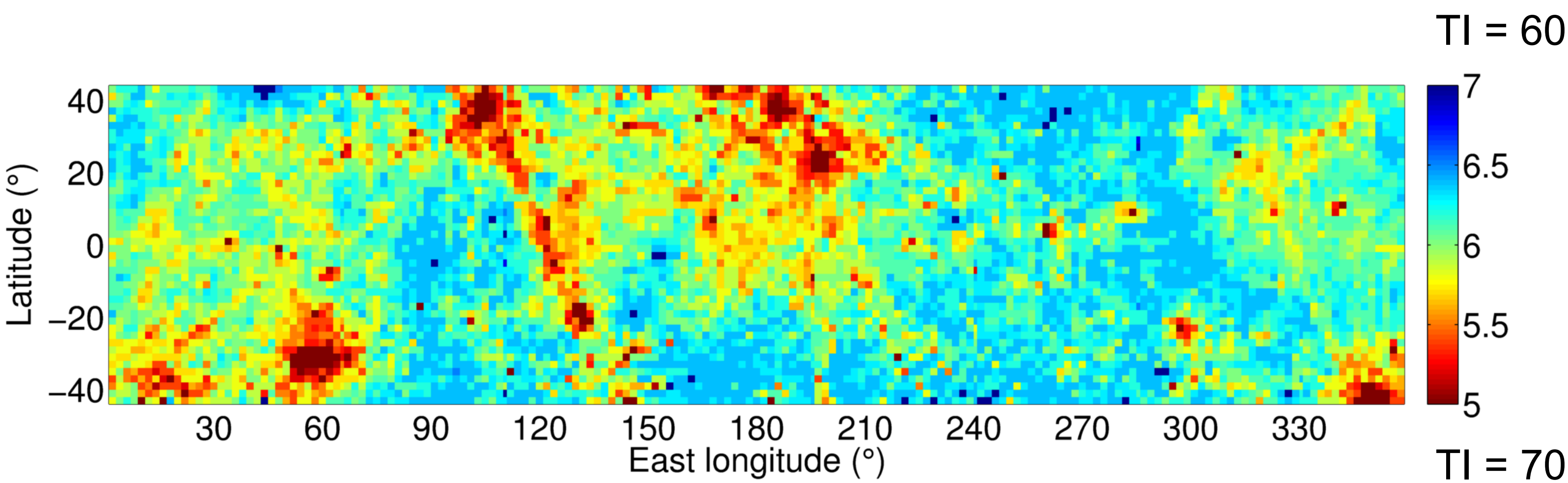
Ghent et al., *Geology* (2014

Sensitivity of Thermal Technique

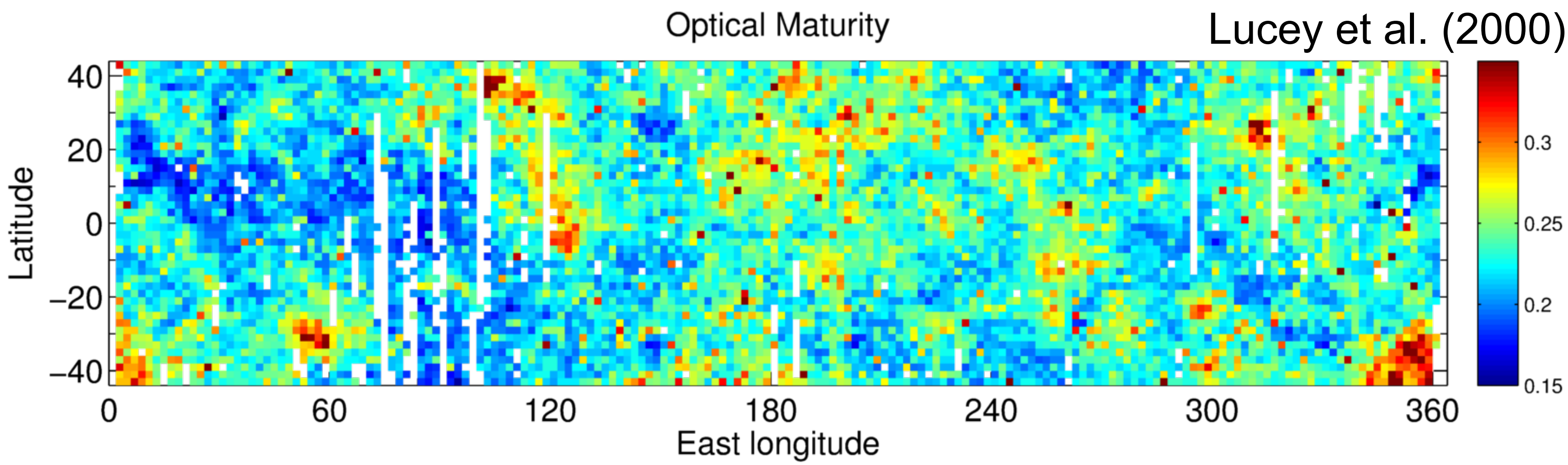


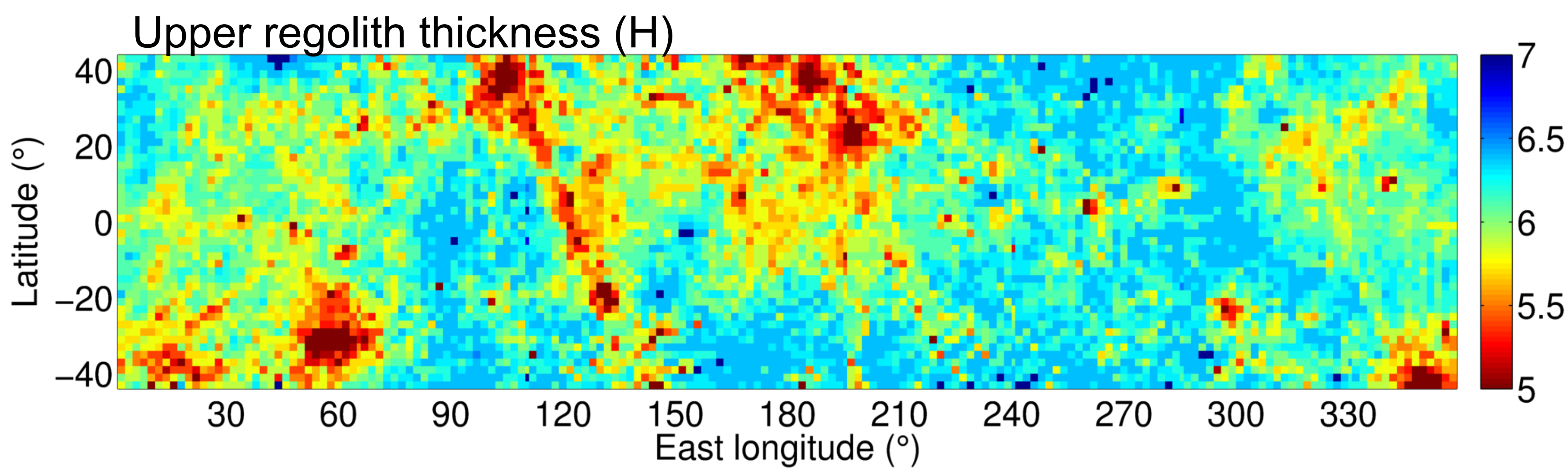
See Equation (15) of Gault et al. (1974)

Global Thermal Inertia Map

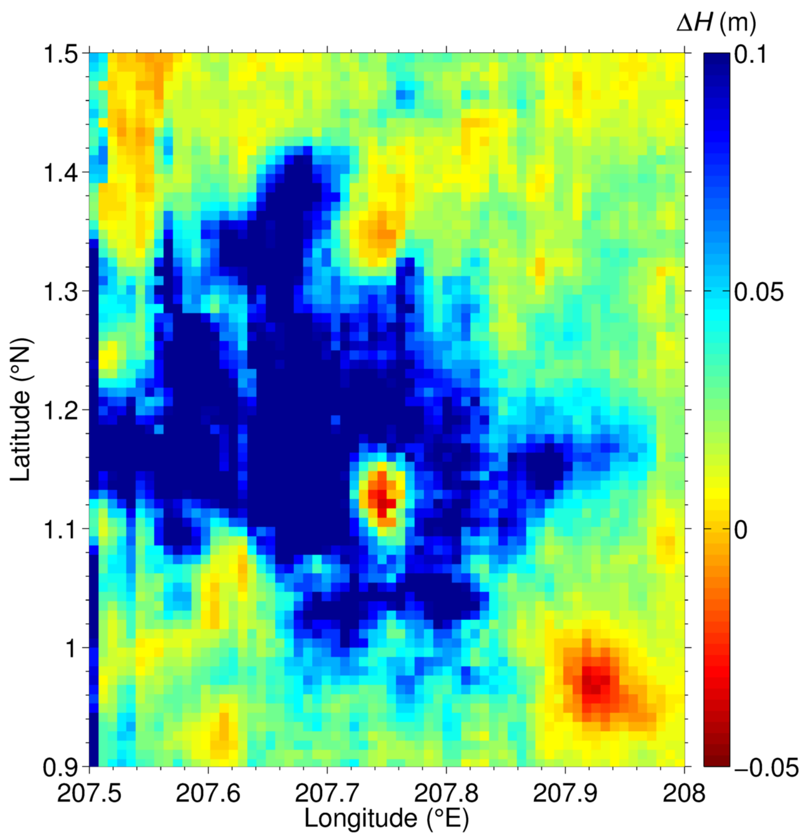


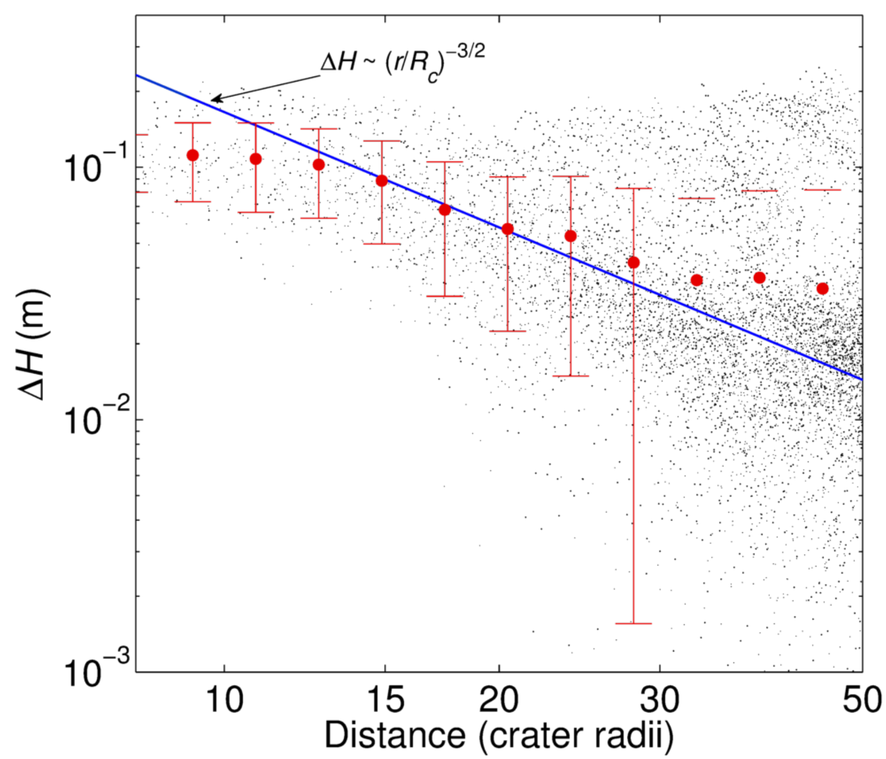
OMAT


Optical Maturity
Lucey et al. (2000)
40
20
0
−20
−40
Latitude
0
60
120
180
240
300
360
East longitude
0.3
0.25
0.2
0.15


Upper regolith thickness (H)
40
20
0
−20
−40
Latitude (°)
30
60
90
120
150
180
210
240
270
300
330
East longitude (°)
7
6.5
6
5.5
5

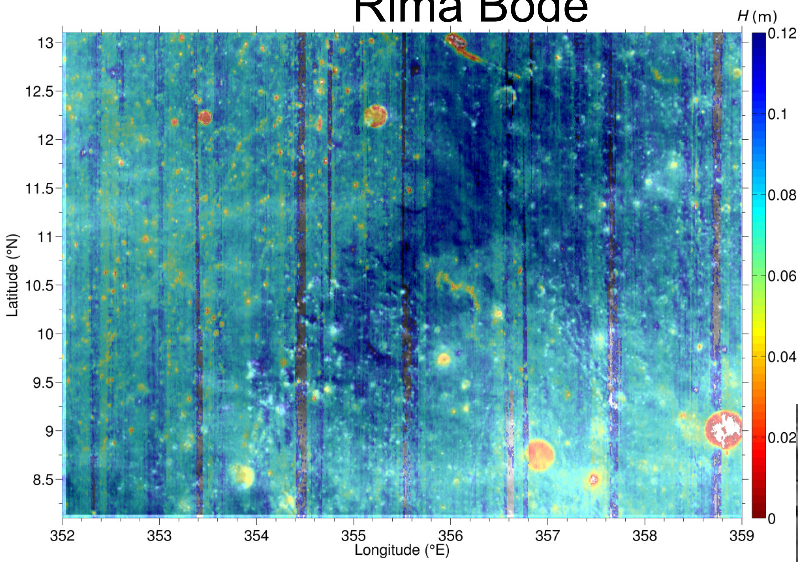
Cold Spots


ΔH (m)
0.1
0.05
0
−0.05
1.5
1.4
1.3
1.2
1.1
1
0.9
Latitude (°N)
207.5
207.6
207.7
207.8
207.9
208
Longitude (°E)


$\Delta H \sim (r/R_c)^{-3/2}$
10^{-1}
10^{-2}
10^{-3}
ΔH (m)
10
15
20
30
50
Distance (crater radii)

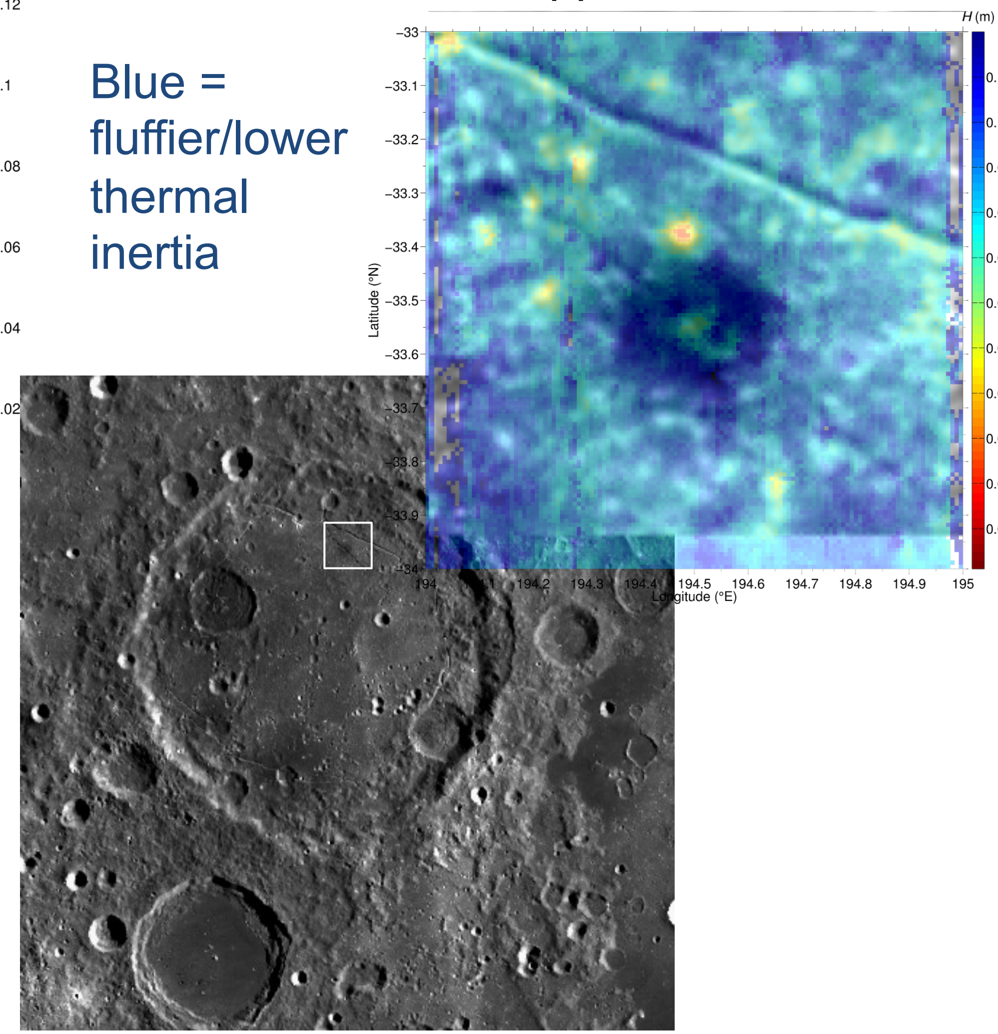
Pyroclastic Deposits

Rima Bode



Blue = fluffier/lower thermal inertia

Oppenheimer



Summary

- Diviner data can be used to separate rock abundance from regolith thermal inertia
- Thermal inertia of upper ~10 cm of lunar regolith is very low (~60-70 SI) and uniform to within ~10% over the lunar surface
- A model with exponentially increasing density in the upper few cm of regolith is consistent with measured cooling curves
- Regolith thermal inertia is correlated with crater age (older = fluffier)
- Global regolith thermal inertia pattern correlated with optical maturity, but some intriguing differences
- Some pyroclastic deposits have low thermal inertia (grain size uniformity?)
- Thermal inertia maps are available for your region of interest!
- Slope effects are prominent and will be removed in a future version

Part of this work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

Backup

Model Regolith Properties

- Thermal conductivity:

$$k_c(z) = k_d - (k_d - k_s)\frac{\rho_d - \rho(z)}{\rho_d - \rho_s}$$

- Density:

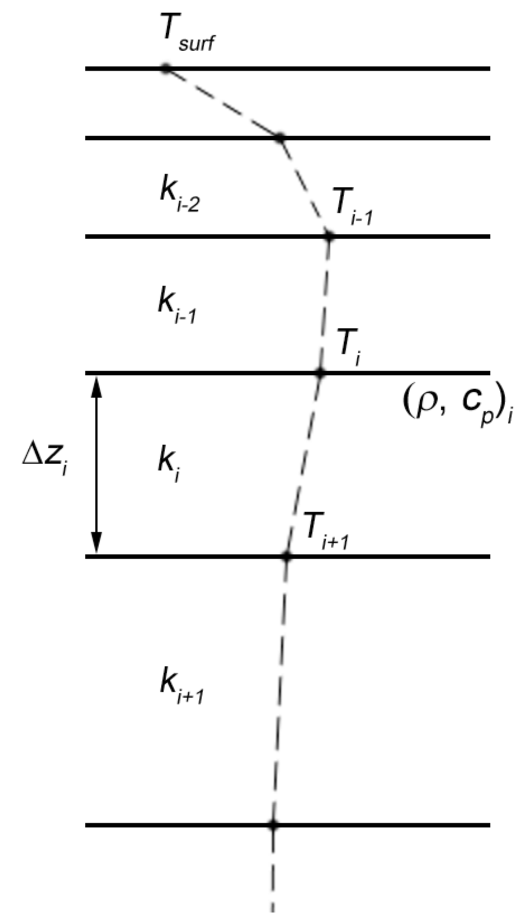
$$\rho(z) = \rho_d - (\rho_d - \rho_s)e^{-z/H}$$

- Albedo:

$$A(\theta) = A_0 + a(\theta/45°)^3 + b(\theta/90°)^8$$

- Radiative "conductivity":

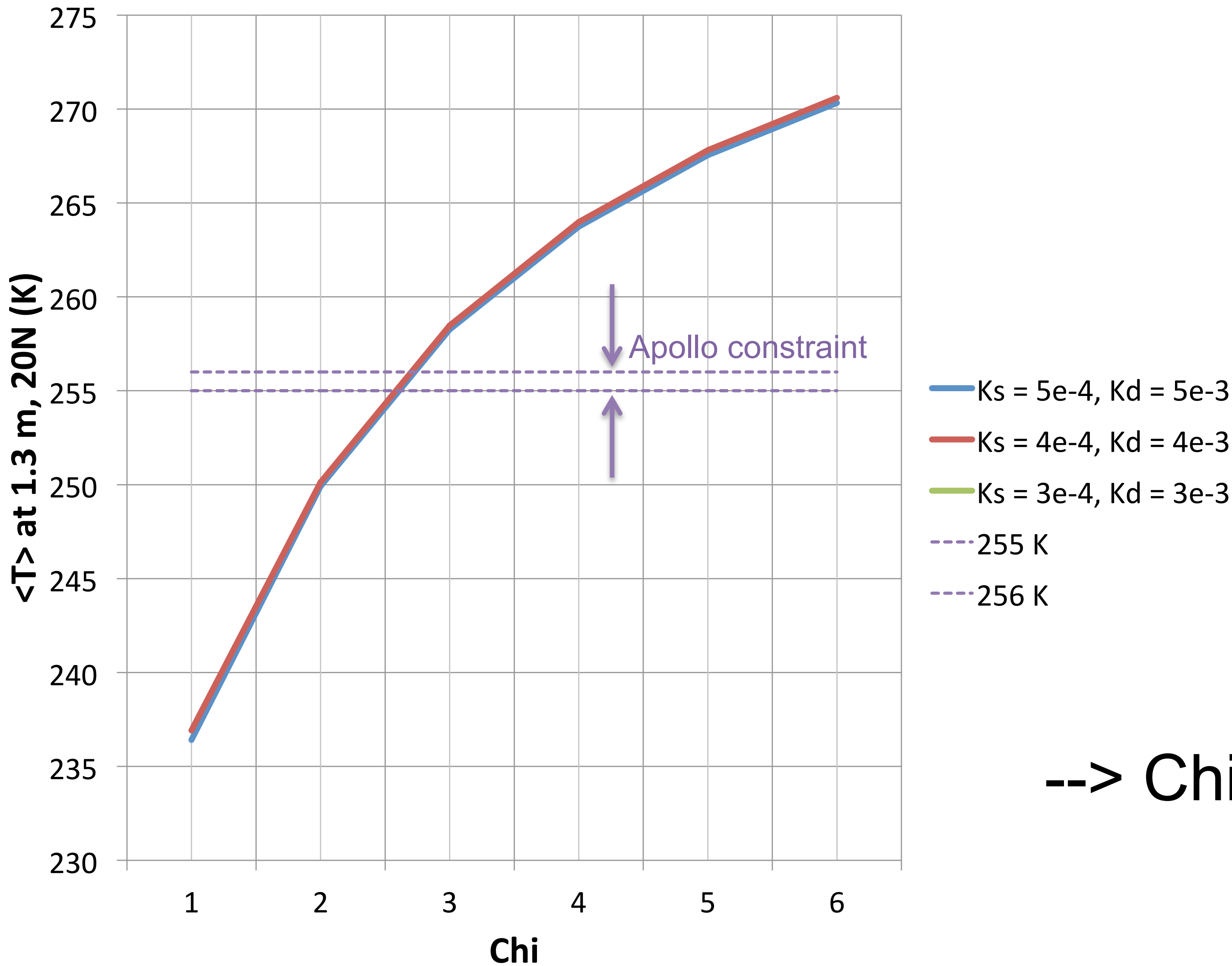
$$k_{total} = k_c\left[1 + \chi\left(\frac{T}{350\text{K}}\right)^3\right]$$



Parameter	Value	Depth/location	Latitude	Reference
Mean annual temperature	**216 (±5 K)**	Surface	20°N	Keihm et al. (1973)
“	**255-256 K**	130 cm	20°N	“
“	**251-252 K**	100 cm	26°N	“
Density	**1100 kg/m^3**	~0 cm	26°N	Carrier et al. (1973)
“	**1600 kg/m^3**	0-30 cm	26°N	“
“	**1800-1900 kg/m^3**	30-60 cm	26°N	“
H-parameter	**0.04-0.1 m**	-	20-26°N	
Thermal conductivity	**0.9-1.5 x10^{-3} W/m/K**	0-2 cm	20°N	Keihm et al. (1973)
“	**0.9-1.3 x10^{-2} W/m/K**	> 50 cm	20-26°N	Langseth et al. (1976)
“	**0.6 x10^{-3} W/m/K**	< 10 cm	equatorial	Jones et al. (1975)
“	**0.6 x10^{-3} W/m/K**	~0 cm	equatorial	Vasavada et al. (2012)
“	**7.0 x10^{-3} W/m/K**	~1 m	equatorial	“
Thermal diffusivity ($k/\rho c$)	**0.4-1.0 x10^{-8} m^2/s**	0-2 m	20-26°N	Langseth et al. (1976)
Radiative “conductivity” (χ)	**1.0 – 3.0**	0-2 m	Low latitude	various

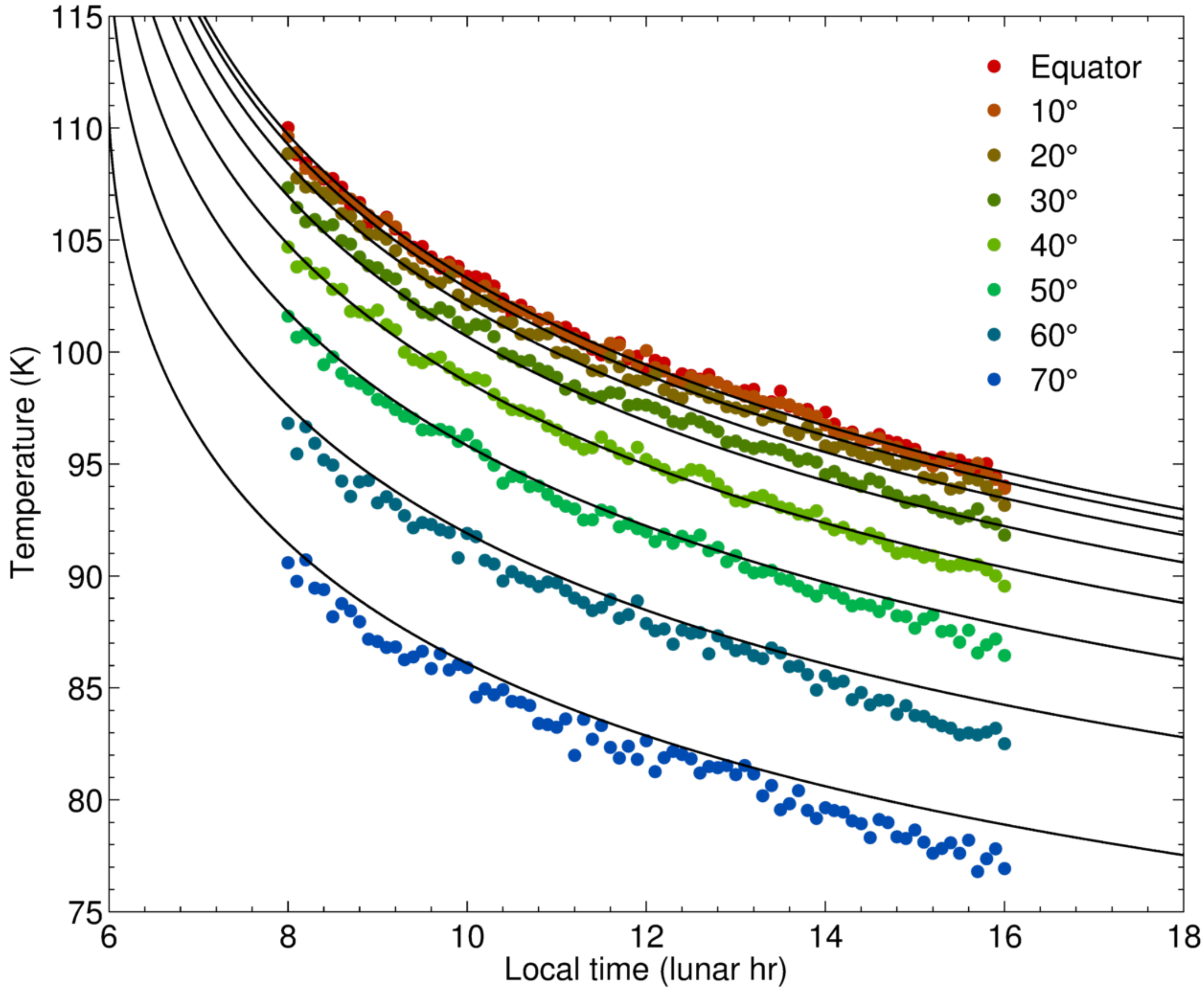
To be added: microwave observations (temperatures at depth)

Radiative Conductivity: The "Chi" Parameter



--> Chi ~ 2.7

Latitude Dependence of Model Fits

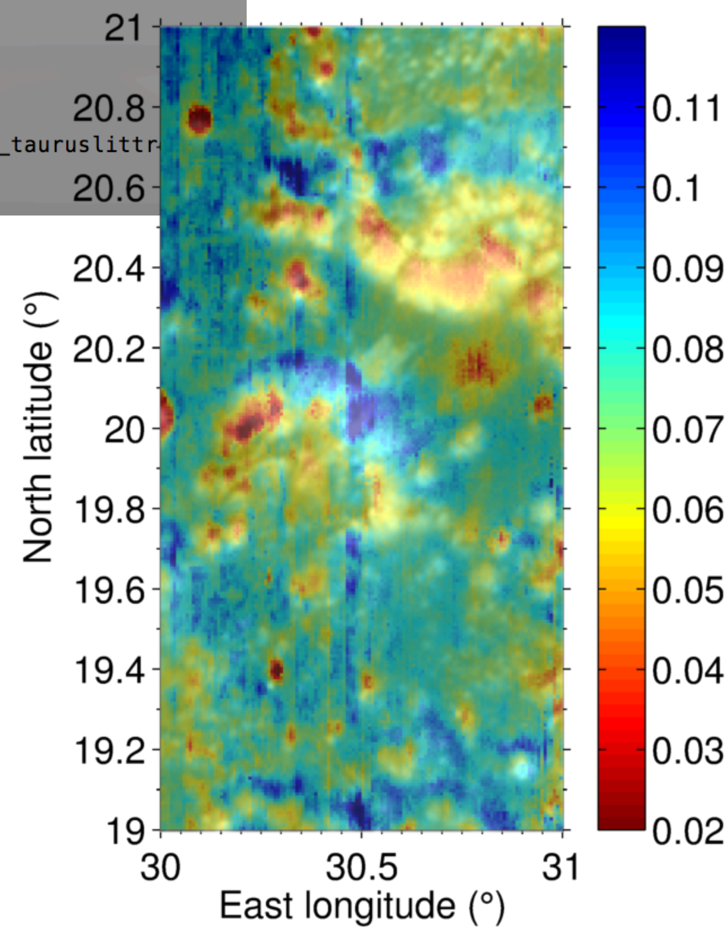


User Guide

```
LMC-026205:~ phayne$ ssh -Y luna1.diviner.ucla.edu
phayne@luna1.diviner.ucla.edu's password:
Last login: Mon Feb 10 17:29:52 2014 from 66.162.254.101
[phayne@luna1 ~]$ mkdir mydir
[phayne@luna1 ~]$ cd mydir
[phayne@luna1 ~/mydir]$ /u/paige/phayne/regolith/hpar

Usage:
<hpar> [lonmin] [lonmax] [latmin] [latmax] [outfile]

[phayne@luna1 ~/mydir]$
[phayne@luna1 ~/mydir]$ /u/paige/phayne/regolith/hpar 30.0 31.0 19.0 22.0 ./h_tauruslittr
Success!
[phayne@luna1 ~/mydir]$
```



- H-parameter maps can be easily generated for your region of interest!
- Feel free to use this tool, but check with me for the latest version and updates often

Weschler et al. 1972

Table 4 Conduction and radiation contributions to thermal conductivity

Material	Particle size, μ	Density, g/cm^3	Solid conduction contribution (B), $w/cm-°K, \times 10^6$	Radiation contribution (A), $w/cm-°K^4, \times 10^{13}$	Ratio of radiation/conduction 200°K	300°K	400°K	Reference
Basalt	10-37	1.36	$21-1.6 \times 10^3/T$[a]	0.88	0.05	0.15	0.34	16
	44-74	1.43	6.10	2.10	0.28	0.94	2.20	16
	37-62	0.79	5.10	1.70	0.26	0.90	2.10	26
	37-62	0.88	6.50	1.70	0.21	0.71	1.70	26
	37-62	0.98	6.20	1.80	0.23	0.78	1.90	26
	37-62	1.10	8.90	1.90	0.17	0.58	1.40	26
	37-62	1.30	12.40	2.40	0.15	0.52	1.20	26
	37-62	1.50	16.20	3.40	0.17	0.57	1.30	26
Quartz	<10	1.00	25.00	3.00	0.10	0.33	0.77	16
	44-74	1.30	33.00	4.20	0.10	0.34	0.81	22
Glass beads	<37	1.2-1.5	9.50	6.30	0.53	1.80	4.20	22
	53-74	1.4-1.7	7.00	3.40	0.39	1.30	3.10	22
	88-125	1.60	3.20	8.50	2.10	7.16	17.00	22
	250-350	1.5-1.6	0.95	13.00	10.90	37.00	87.70	22
	590-840	1.6-1.8	(-0.66)[b]	26.00	...	...	...	22
	44-62	1.40	4.70	3.00	0.51	1.70	4.10	16
	10-20	1.50	4.70	2.80	0.48	1.60	3.80	23
	38-53	1.50	4.50	3.30	0.59	1.90	4.70	23
	125-243	1.30	0.07[c]	5.40	61.70	208	493	23
Pumice	10-37	...	5.10	3.10	0.49	1.70	3.90	16
	44-74	...	2.50	3.60	1.10	3.80	9.10	16
Olivine	<74	1.37	10.80	1.30	0.096	0.33	0.77	22

[a] Data were best fit by Eq. (7c).

[b] A negative value of the conduction term was obtained; this is not possible but indicates that conduction was small.

[c] Several values ranging from -0.09 to +0.15 were obtained for three similar samples; the radiation term varied from 3.1 to 5.4 for these samples.

Density-conductivity relationships